FINAL REPORT

For Project entitled:

Personal Air Vehicle Exploration Tool and Modeling

Under Contract NAS3-00179/L-70884-D

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Executive Summary

ASDL has completed the current phase of research to "continue development of analysis tools for Personal Air Vehicle Exploration (PAVE) system studies", under NASA Langley's Revolutionary Aerospace Systems Concepts (RASC) program. ASDL has completed the current phase of the research and the results are described in this final report (fulfilling contract NAS3-00179/L-70884-D). The developed tools are intended to explore fundamental feasibility questions about doorstep to doorstep transportation solutions involving both air and ground travel. Key metrics for establishing fundamental feasibility are the reduction of personal travel time, the increase in travel mobility, and the ability to achieve a market share at an affordable cost while satisfying societal constraints. Sensitivities of several driving parameters for these metrics have been computed. Finally, an exploration of uncertainty using ASDL's probabilistic methodology was conducted. The research completed and prototype tools developed facilitate the assessment of PAV system concepts and guide the further development and analysis of concepts within these architectures.

The project was organized into four tasks, including: "Methodology development of a probabilistic PAVE system metric sensitivity tool", "Advanced Concept Rotorcraft Development", "Methodology development for circulation control channel wing performance", and "Methodology development of ducted fan/propeller performance, weight, and noise". This executive summary highlights key findings, while detailed results under each of these four tasks are contained in this report.

The first task resulted in the successful enhancement and expansion of the PAV Benefits Exploration Tool. This tool truly enables the consideration of fundamental feasibility questions involving doorstep to doorstep transportation solutions and the sensitivity of key metrics, such as net present value and travel time, to a wide array of vehicle, system, and operational environment variables. Several operational use scenarios were created to exemplify the capability of the Benefits Exploration Tool in exploring "What-If" questions and identify the optimal areas for technology investment. Further, a web-based implementation of the tool was developed, with specially designed functionality areas for both engineers/managers) and the general public (a person who wants to explore what PAVs might mean for them). This capability for distributed PAV exploration and the creation of "living system studies" was a primary desire of the sponsor. The Response Surface Method (RSM) was employed to create response surface equations that facilitate the communication of the results to managers and decision-makers.

The second task resulted in the successful development of a unified tradeoff environment (UTE) for light helicopter and autogyro type rotorcraft as PAV vehicles. The UTE allows tradeoff of performance requirements and technology levels simultaneously. Portions of the UTE have been integrated into the PAVE web site described above and later in the report in more detail. A range of both evolutionary and revolutionary concepts that may allow dramatic improvements in noise, cost, and speed were summarized as well. Further, a more detailed analysis was conducted on a particular concept, the CarterCopter, which emerged as an interesting PAV that demonstrated some impressive flight test results early in 2002. The CarterCopter autogyro concept was modeled and simulated in ASDL's rotorcraft sizing code. Although this analysis is as yet incomplete, the initial findings indicate that this concept (which is characterized most prominently by flight at high advance ratios) has the real possibility of achieving the unique combination of extremely short takeoff and high cruise speed attributes that would make it an attractive PAV and worthy of continued study.

The third task resulted in the successful expansion and improvement of a quick and easy to use spreadsheet aerodynamic tool for channel wing, circulation control configurations. The expansion included the incorporation of Blick's theory for power-on conditions (including airfoil library) for use in estimating force coefficients. The overall usability of the tool was also improved. Attempts to further enhance the tool through using of parametric geometry, vortex lattice analysis for power-off conditions failed to produce acceptable results and is not included. The incorporation of planar wing data did not occur, since the sponsor could not provide the data.

The fourth task resulted in the successful creation of a new analysis tool for computing the performance, weight, and noise of propellers and ducted fans (e.g. QFAN, developed by Hamilton Standard). The analysis routines in the program are derived primarily from a series of detailed design data books that were also originally developed by Hamilton Standard. The program is accompanied by a list of important assumptions that a user needs to be aware of as well as a simplified User's Guide. The channel wing and ducted fan tools are of specific interest to this class of vehicle due to the increased performance of these systems at low speed, permitting short field operation and closer proximity operation.

Additional results and findings for each major task are summarized in the body of this report along with a description of how to understand and employ the tools developed.

1. PAV Benefits Assessment Methods and Tools

1.1. On-Demand Mobility Methodology Development and Implementation

Motivation

The overall model of the PAV environment is categorized into a microscopic model and a macroscopic model. The Benefits Visualization Tool is an integration and implementation of equations, assumptions, and vehicle data that serves as the building block for the microscopic model. This tool provides a Unified Tradeoff Environment (UTE) that simulates the effectiveness of a PAV for a single user's travel and eventually forms the foundation for a system dynamics study of the larger system-of-systems, which is the long term objective of this line of research.

The Benefits Visualization Tool has been constructed from the outset of being robust and receptive to variations in applications. As the PAVE program matures, the tool has evolved into a platform that would not only be applicable for alternative business models air vehicles, but would also allow multiple expressions of mobility improvement efforts.

Technical Approach

The Benefits Visualization Tool consists of three main components: interface, performance computations, and economic computations.

Interface

The interface component acts as a mediator between the user and the benefits visualization tool, and constitutes of three profiles: vehicle/mission, economics, and location. The microscopic model will compute the travel performance for the ind vidual user based on the specified vehicle/mission profile and the travel economics based on the specified economic profile. Meanwhile, given a specified user's location profile, a local traffic capacity model based on that profile can be created using a simulation technique such as system dynamics or Agent-Based Simulation. This larger model serves as the platform for the macroscopic mass traffic capacity model.

Vehicle/Mission Profile

The Vehicle/Mission profile interface allows user to select the desired vehicle options and mission options for analysis. PAV options have been categorized into 4 groups based on their takeoff and landing distance; VTOL (100 ft), SSTOL (500 ft), STOL (1000 ft), and CTOL (2000 ft). Definition of each PAV group is provided in Nomenclature section. Each group is divided into two modes; single mode and dual mode PAVs. Single mode PAVs are PAVs that require alternate ground vehicles such as cars or taxis to transport users to the PAV facilities. Dual mode PAVS are PAVs that operate as ground vehicles as well as air vehicles. Each mode is then divided into two options; fast and slow PAVs. Hence, there are a total of 16 PAV options as shown in Figure 1 below:

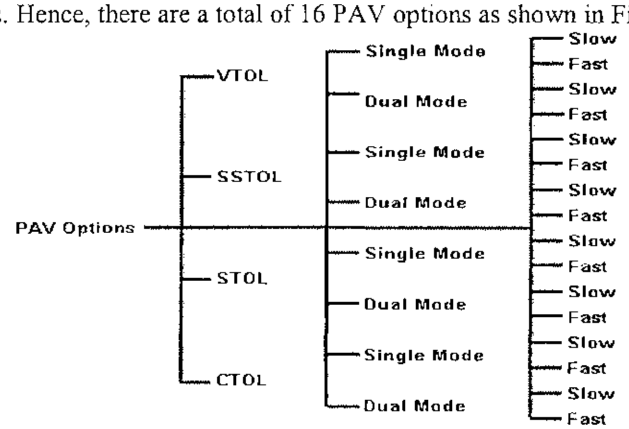


Figure 1: Categorization of PAV Options

The PAV generic mission profile is depicted in Figure 2. Each PAV option must complete the main mission from access portal A to access portal B, that is, from one airport location to another. Selection of a single mode PAV is accompanied by either a personal car or a rental car to get to and from the airport. Meanwhile, selection of a dual mode PAV does not require additional ground vehicle. For comparison sake, a user is able to select a ground vehicle (personal car or rental car) and a commercial airline to complete the main mission on top of the 16 PAV options. In this way, the resulting tool can truly be considered an intermodal options analysis.

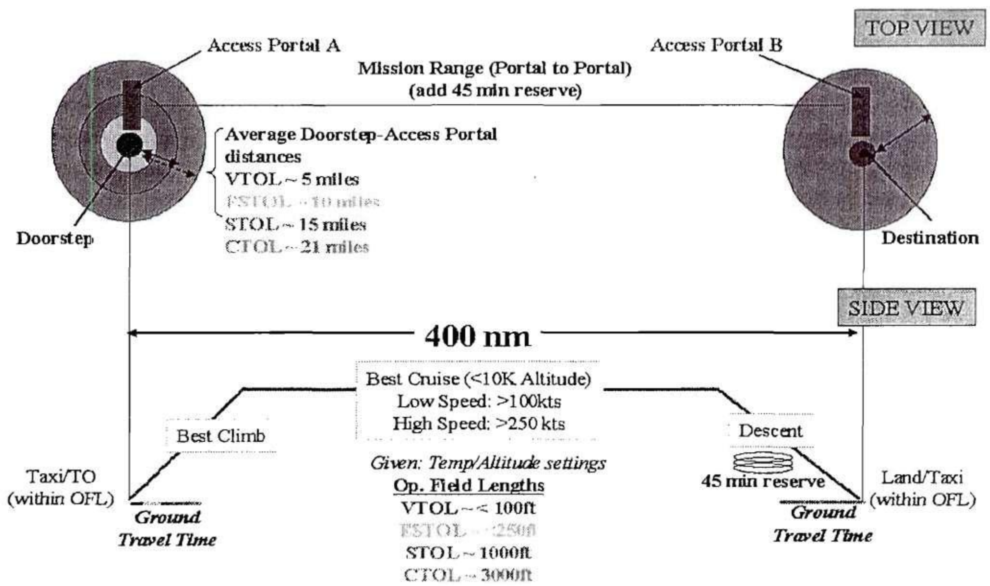


Figure 2: PAV Mission

The next important interface is the mission profile, which identifies the profiles for the user's typical travel. The inputs options are shown in Figure 3 below. The range for the typical distance of 100 to 500 nm is selected based on the most commonly flown distance for general aviation and SATS aircraft. Trips made per week refers to one-way trips made whether to and from the workplace for the whole week. For instance, a typical 5 working days week constitutes of 10 trips per week. The number of 'PAV-pooling' passengers refers to the number of passengers onboard that share the direct operating cost of the PAV, similar to sharing gas cost in a car pool. Analysis presented later will show the dramatic impact reductions in DOC can have on the overall PAV option affordability.

Mission Options	*Selection*	
Typical Range (100 - 500 n.m.)	200	n.m.
Trips Made Per Week (6-22)	10	trips/week
Number of 'PAV-pooling' passengers (max 4)	2	passengers

Figure 3: Mission Profile Inputs

The final set of vehicle/mission profile options concerns the vehicle economics. The user is allowed to determine the specific vehicle financing terms, as shown in Figure 4, which will significantly influence the viability of the PAV. These financing options are down-payment for the PAV, loan interest rate, loan period, and predicted life span of the PAV.

Vehicle Economics Options	*Selection*	
Downpayment (as fraction of vehicle acq. cost)	15	%
Loan Interest Rate (Annual)	9	%
Loan Period	12	years
Predicted Lifespan of Vehicle (50 years max.)	40	years

Figure 4: Vehicle Economics Profile Inputs

Information obtained from this profile will be used to compute the performance of the PAV option relative to a baseline transportation mode, as discussed in later section.

Economic profile

The current economic model is an individual purchase model. Other models, such as fractional ownership and air taxi are also being investigated. This economic profile interface requests financial and economic information of the individual user in order to compute the viability of the PAV option. This is because the measure of merit for the microscopic model is based on the 'value of time saved' concept, which will be discussed later. As shown in Figure 5, a user is allowed to input his/her annual household income as well as values for predicted annual percentage increase/decrease of annual household income for the first 15 years from present day, in steps of 5 years.

My current annual income (in US Dollar) is:	$90,000 <input top>
Predicted income change per year in first 5 years (+/-) is :	5.0% <input top>
Predicted income change per year in following 5 years (+/-) is :	[illegible] <input top>
Predicted income change per year in following 5 years (+/-) is :	5.0% <input top>

Figure 5: User Economic Profile Inputs

Information obtained from this profile and the performance computation based on vehicle/mission profile will be used to compute the 'value of time saved' by utilizing the PAV option as compared to a baseline transportation mode. This metric will be the measure of merit for the microscopic model.

Location profile

The location profile interface requests the user's typical origin and destination information, in terms of population density, weather, and infrastructure availability. The population density is categorized based on U.S. Census categorization. Meanwhile, weather is categorized into six weather group regions in the U.S based on studies by the Office of Safety and Mission Assurance (OSMA). Infrastructure availability is categorized more intuitively by simply asking the user to rate the infrastructure availability in a scale from 1 to 5, with 4 being least available and 5 being "Uncertain" (where a defaulted value will then be used).

Code	Description
Metro counties:	
1	Central counties of metro areas of 1 million population or more.
2	Counties in metro areas of 250,000 to 1 million population.
3	Counties in metro areas of fewer than 250,000 population.
Nonmetro counties:	
4	Urban population of 20,000 or more.
5	Urban population of 2,500 to 19,999.

Figure 6: Population Density Categorization

Code	States
1	CT, MA, ME, NH, NJ, NY, PA, RI, VT, WV
2	AL, AR, DE, FL, GA, KY, LA, MD, MO, MS, NC, SC, TN, VA,
3	IL, IN, MI, MN, OH, WI
4	IA, ID, MT, ND, NE, KS, SD, UT, WY
5	AZ, CA, CO, NM, NV, TX
6	OR, WA

Figure 7: Weather Region Categorization

Performance Computations

As mentioned earlier, vehicle performance is dictated by parameters such as vehicle speed, empty weight, fuel weight, single or dual mode, takeoff field length categories, etc. These parameters will be used to compute the key performance metrics; Doorstep-to-Destination Time.

Doorstep-to-Destination Time (D-D Time)

Doorstep-to-destination time refers to the total travel time from the origin location to the destination location, including all the delay times and travel times from origin and destination to access portals. For a PAV "world", the access portal refer to any facility that is capable of handling a PAV, ranging from helipads to private runways to regional airports. Breakdown of the D-D time is shown below:

Equation 1: D-D Time Computations

$$\text{D - D Time} = \alpha + \beta + \delta + \varepsilon + \varphi$$

$$\text{where } \alpha = \text{Travel Time}_{\text{Doorstep to Portal A}} = \frac{\text{Ground Distance}}{\text{Avg. Ground Vehicle Speed}}$$

$$\beta = \text{Travel Time}_{\text{Wait Time at Portal A}} = \text{Vehicle Specific}$$

$$\delta = \text{Travel Time}_{\text{Portal A to Portal B}} = \frac{\text{Travel Distance}}{\text{Avg. Vehicle Air Speed}}$$

$$\varepsilon = \text{Travel Time}_{\text{Wait Time at Portal B}} = \text{Vehicle Specific}$$

$$\varphi = \text{Travel Time}_{\text{Portal B to Destination}} = \frac{\text{Ground Distance}}{\text{Avg. Ground Vehicle Speed}}$$

Assumptions for D-D Time Computation

1. The 16 modes of PAV, divided into groups of 4 main categories (VTOL, SSTOL, STOL, and CTOL) have specified average distances from doorstep and destination to portals of 5, 10, 15, and 21 miles respectively. Average distance to a commercial airport is assumed to be 30 miles.
2. Due to environmental and operational constraints, it is assumed that dual mode PAVs will not be allowed to operate from a populated residential or business location in spite of the idealized 'operable from anywhere' concept of dual mode vehicles.
3. The wait time at access portals is fixed at 30 minutes for each of the PAV option whereas for commercial airlines option, the wait time is fixed at 2 hours upon departures and 1 hour after arrivals.
4. Average speed of ground vehicles to and from access portals is specified as 50 mph. Average speed of personal automobile as a main travel mode is specified as 65 mph. The ground speeds of dual mode PAV are extracted from the vehicle database.

Economic Computations

Cash Flow Analysis

In the engineering field, cash flow analysis is most commonly used in describing the predicted profitability of a project. Results from this analysis are depicted in a cash flow graph as a function of time (unit of time may be days, months, years, etc depending on the size and scale of the project/investment). This graph provides crucial information such as break-even point, net profit, sunk cost, capital investment, payback period, profitability, and utilization period to aid decision-makers in making intelligent and financially-sound decisions. Definitions for important economic terms relevant to the cash flow analysis are provided below (see Ref. 3 and Ref. 4 for detailed definitions and equations):

Cash flow is the difference between receipts and expenditures, which may have either negative (i.e. expenditures exceeds receipts) or positive values (i.e. receipts exceeds expenditures) at any point of time.

Cumulative cash flow is the accumulation of cash flows since the beginning of the project/investment to the termination of the project/investment, which is also the y-axis data plot of the cash flow analysis graph.

Break-even point is the first point of time when cumulative receipts exactly equates cumulative expenditures, where value of cumulative cash flow at that instance of time is zero.

Net profit is the value of a positive cumulative cash flow in the cash flow analysis at the final point of time when the project/investment is salvaged or terminated.

Sunk cost is the most negative value of cumulative cash flow in the cash flow analysis, typically referring to cumulative cash flow at the final point of the capital investment.

Capital investment period refers to the period when capital investments are being paid for, which is from the beginning of the project/investment to the point of time when sunk cost is incurred.

Payback period refers to the period when the sunk cost is gradually paid back by excessive cumulative receipts, which is right after capital investment has been totally accounted for to the break-even point of time.

Profitability refers to the period when the project/investment is having a positive cumulative cash flow, which is from the break-even point to the final point of time in the cash flow analysis.

Utilization period refers to the period when the project/investment is active and generating cash flows.

Economics Assumptions for PAV Concept

Similar to any other business project or investment, the economic viability of a PAV concept can be depicted using a cash flow analysis. Accompanying the cash flow analysis for the PAV concept is a list of critical assumptions that define the economics of the concept:

1. All cash flows are discounted to present value based on real interest rate, which includes the effects due to inflation. Values for a estimated annual inflation rate and annual nominal interest rate are specified to compute the expected annual real interest rate as follows :

Equation 2: Real Interest Rate Computation

$$r_o = \frac{r - f}{1 + f}$$

where r_o = real interest rate
r = nominal interest rate
f = inflation rate

2. Cumulative cash flow analysis for users' selected PAV options as well as the baseline vehicle options are computed based on the selected vehicle's performance.
3. The forms of expenditures for the cash flow analysis are vehicle financing (interests and installments) and direct operating costs. The form of receipts for the cash flow analysis is the value of time saved by utilizing a PAV option as compared to a baseline transportation mode (further discussed in later sections). The cumulative cash flow analysis for the baseline transportation mode is comprised of only expenditures because there is no value of time saved.
4. There are two baseline transportation modes; personal automobile and commercial airliner. For travel distances from 100 to 500 nm, an optimum baseline is selected on the basis of shortest travel time and lowest travel costs (see Assumption 5 below) such that the comparisons between baselines and PAV options are most accurate. Figure 8 shows that optimal travel time for distances from 100 nm to 300 nm is by car whereas commercial airliners optimizes travel time for distances greater than 300nm. Table 1 further reinforces that statement by showing that driving is cheaper for distances from 100 nm to 300 nm whereas flying is more cost effective for distances above 300 nm. Hence, the baseline transportation mode are personal automobiles for distances ≤ 300 nm and commercial airliners for distance >300 nm.

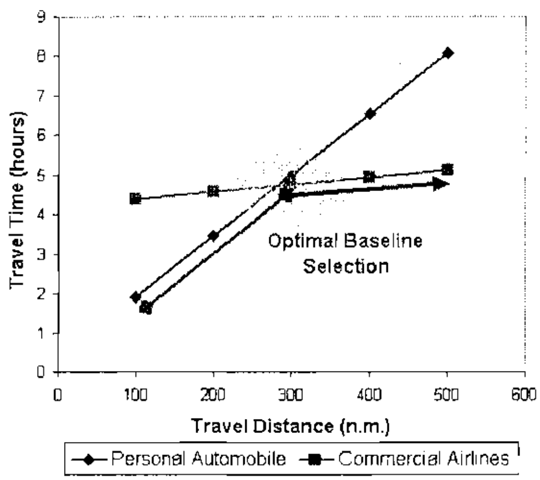


Figure 8: Travel Time Analysis for Baseline Modes

Table 1: Travel Cost Analysis for Baseline Modes

Travel Distance (nm)	100	200	300	400	500
Cost Difference Relative to Car ($)	+116.79	+76.22	+36.12	-3.52	-42.69
Optimal Option	Car	Car	Car	Plane	Plane

5. The cost of utilizing personal automobiles is rated at $0.35 per statute mile of travel[5]. Cost of utilizing commercial airlines is computed from a quadratic polynomial fit of an array of current air ticket price list referenced from Ref. 6. Cost of utilizing rental cars or cabs to and from commercial airports is estimated at $2.00 per statute mile of travel as an averaging value for first mile cost (varying from $2 to $3) and $0.40 per quarter mile rate [7,8].
6. Salvage value for vehicle at the end of vehicle utilization is fixed at 15% of initial vehicle acquisition price.

There are two versions of cumulative cash flow analysis; direct cumulative cash flow and adjusted cumulative cash flow. Direct cumulative cash flow is computed directly using data from the vehicle database for both PAV options and baseline options. The direct cumulative cash flow of PAV options may show either a net profit or net loss relative to the baseline cash flow, indicating a profitable or unprofitable PAV option (see Figure 9). Adjusted cumulative cash flow is computed for the PAV options relative to the selected baseline option. This is based on the assumption that cash flow for the baseline transportation mode is regarded as incurred cost to provide users' mobility. Hence, subtracting this incurred cost from the PAV option cumulative cash flow yields an adjusted cumulative cash flow that reflects the relative financial gain or loss due to the adoption of a PAV concept (see Equation 3 and Figure 10). Adjusted break-even point occurs when the PAV option breaks even with the baseline cash flow in Figure 9, and is equivalent to the conventional break-even with the X-axis in Figure 10.

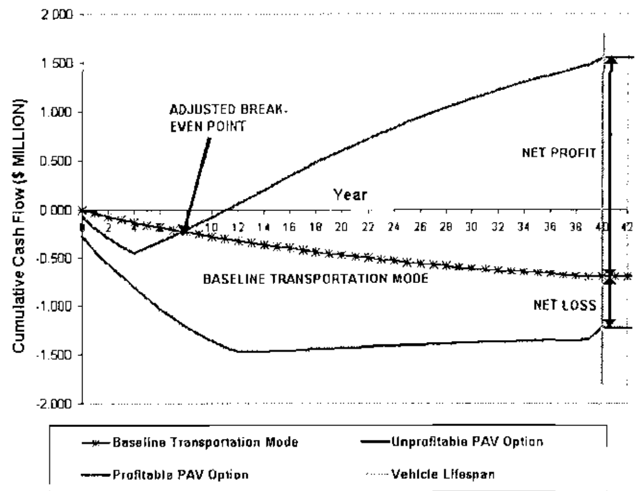


Figure 9: Direct Cumulative Cash Flows

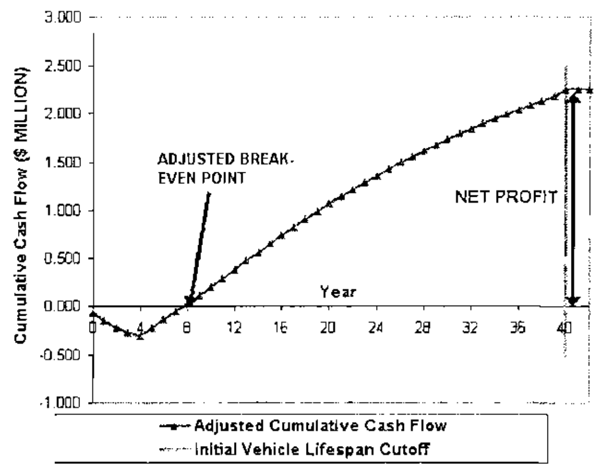


Figure 10: Adjusted Cumulative Cash Flow

Equation 3: Adjusted Cumulative Cash Flow Computation

$$\begin{aligned}&\text{Adjusted Cumulative Cash Flow, ACF}\\&= \text{PAV Option Cum. Cash Flow - Baseline Cum. Cash Flow}\\&\text{where ACF can have negative OR positive values}\end{aligned}$$

Value of Time Concept

As mentioned earlier, the only form of receipts for the cash flow analysis is the value of time saved by utilizing a PAV option as compared to a baseline transportation mode of either personal automobiles or commercial airlines. Value of an individual's time is a continuously debatable issue as one's worth of time truly depends on his/her personal evaluation and character. Nevertheless, it is reasonable to impose a numerical value of time based on how much money an individual makes on a regular working hour. Hence, the equation for value of time is:

Equation 4: Value of Time Computation

$$\begin{aligned}&\text{Value of Time (in units of dollars per hour)}\\&= \frac{\text{Annual Income}}{\text{2080 working hours per year}}\end{aligned}$$

For example, the value of time for an individual making $52,000 a year is $25 per hour.

Given a PAV option and a selected baseline option, the Doorstep-to-Destination times can be computed using the equation in Equation 1 along with the relevant assumptions and data from the vehicle database. Using these D-D travel times of the baseline and the PAV, a metric named Vehicle Time Saving Index (VTSI) is created:

Equation 5: Vehicle Time Saving Index (VTSI) Computation

$$\text{VTSI} = \frac{\text{D - D Time}_{\text{Baseline}} - \text{D - D Time}_{\text{PAV Option}}}{\text{D - D Time}_{\text{PAV Option}}}$$

VTSI is a dimensionless value that represents the amount of time saved for every utilization hour of a PAV option as compared to utilizing the baseline option. A negative value for VTSI indicates that the PAV option is slower than the baseline and should not be considered in the first place. VTSI will then have a value of zero. From the definition of VTSI and value of time, the value of time saved by utilizing a PAV option can be simply defined as:

Equation 6: Value of Time Saved Computation

$$\begin{aligned} &\text{Value of Time Saved (in dollars)} \\ &= \text{VTSI} * \text{Hours of Utilization} * \text{Hourly Value of Time} \end{aligned}$$

Cash Flow Computation for PAV Concept

With the economics assumptions and value of time concept described above, the cumulative cash flows for PAV concepts are computed as shown Equation 7.

$$\begin{aligned} \text{Cumulative Cash flow} &= \text{Cumulative Profits - Cumulative Costs} \\ &= [\text{VTSY} + \text{Cumulated Profits}] - [\text{TCPY} + \text{Cumulated Costs}] \end{aligned}$$

$$\begin{aligned} &\text{where:} \\ &\text{VTSY} = \text{Value of Time Saved per Year for current year} \\ &= \left(\frac{\text{Value of Time}}{\text{1 hour}}\right) * \left(\frac{\text{Hours Saved by using PAV per year}}{\text{1 year}}\right) \\ &= \left(\frac{\text{Income Fluctuation Rate} * \text{Annual Income}}{\text{2080 working hours per year}}\right) \\ &\quad * \left(\text{Hours Saved per day} * \frac{\text{260 working days}}{\text{1 year}}\right) \end{aligned}$$

$$\begin{aligned} &\text{TCPY} = \text{Total Cost Per Year} \\ &= \text{Annual Capital Payment} + \text{Adjusted Annual Direct Operating Cost (DOC)} \\ &= (\text{Annual Interest Payment} + \text{Annual Installment}) + \text{Adjusted Annual DOC} \\ &= \left[(\text{Loan Interest Rate} * \text{Loan Balance}) + \frac{\text{Post Downpayment Balance}}{\text{Loan Period, n}} \text{for n years}\right] \\ &\quad + \left[\text{Real Interest Rate} * \frac{\text{DOC}}{\text{1 hour}} * \frac{\text{Hours}}{\text{1 Trip}} * \frac{\text{Number of Trips}}{\text{1 week}} * \frac{\text{52 weeks}}{\text{1 year}}\right] \end{aligned}$$

Equation 7: Cash Flow Computation

UNIFIED TRADEOFF ENVIRONMENT (UTE)

The various equations are merged to form a benefits visualization tool. This tool's purpose is to provide a unified tradeoff environment that facilitates the parameterized requirements forecasting and benefits estimation of a Personal Air Vehicle Exploration (PAVE). The successful accomplishment of these two tasks forms the foundation for a system dynamics study of the larger system-of-systems, which is the long term objective of this line of research. This unified tradeoff environment must be able to integrate the performance and economic attributes such that an Overall Evaluation Criterion (OEC) can be computed. This is done via the value of time saved concept, which translates the PAV option D-D time (which is totally dictated by vehicle performance) to a relative economical gain or loss in the cash flow analysis. The UTE must also be able to provide a parameterized environment where sensitivity of the system level attributes and design parameters can be studied. These two characteristics of the UTE will enable the desired forecasting and scenario modeling of the PAVE.

TASK 1: PARAMETERIZED PAVE REQUIREMENTS FORECASTING

It is of interest to be able to quickly and accurately determine the PAV requirements to achieve profitability for a given segment of users. The technology and infrastructure assumptions used is a representative of a future time when PAVs are widely accepted and used by the general public, much like automobiles in current time. Using Response Surface Methodology (RSM) [4] and the benefits visualization tool as the analysis engine, this parameterized PAV environment is created with the main objectives being:

i. To revalidate relationships between performance and economics attributes as prescribed by the assumptions made
ii. To generate PAV requirements for use by vehicle designers
iii. To investigate the sensitivities of the key outcome metrics to the performance and economic computations
iv. To identify key technology areas for succession of a PAV concepts based on objectives i and ii

A list of 7 parameters is identified through brainstorming and trial runs, as shown in Table 2. These parameters are selected based on their sensitivities to the computation of travel time and value of time saved. The ranges are carefully selected to ensure that the requirements space exploration covers all potential outcomes and includes interactions between the variables.

Table 2: Requirement Parameters and Ranges

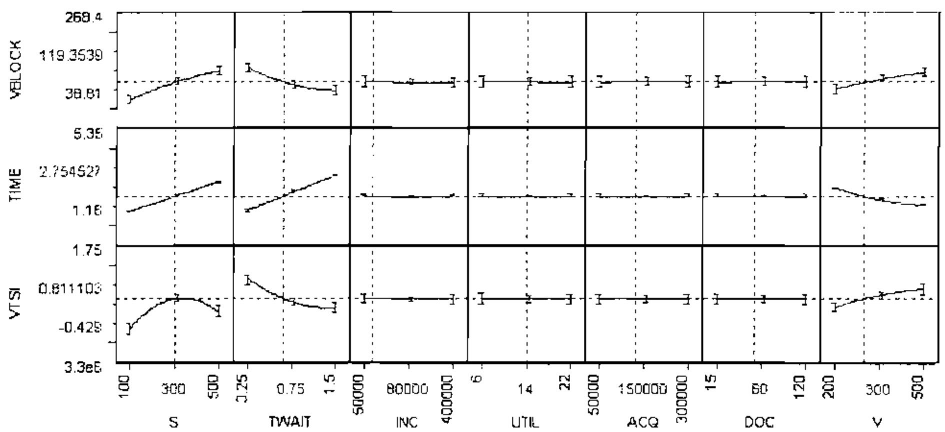
Description	Symbol	Unit	Lower	Baseline	Upper
Mission Requirements					
Mission Range	S	mi	100	300	500
Wait Time at Portal	TWAIT	hour	0.25	0.88	1.50
Vehicle Requirements					
Vehicle Air Speed	V	mph	200	350	500
Acquisition Cost	ACQ	$	50000	175000	300000
Direct Operating Cost/Hour	DOC	$/hr	15	68	120
User Requirements					
Personal Income	INC	$	75000	237500	400000
Utilisation	UTIL	trips/week	6	14	22

With these 7 variables, a 3-level Design of Experiment is created and a total of 79 simulation runs were made. The metrics of interest are recorded and used to generate the Response Surface Equations (RSE), as shown in Table 3. One of the responses that are of primary interests is adjusted break-even year (see earlier section for definition). However, due to the fact that a significant number of cases may not break-even when utilizing a PAV option, this metric will have a poor model fit and hence, cannot be used as a response. Instead, adjusted cumulative cash flows at year 5, 10, 20, and 30 are kept tracked of to depict adjusted break-even point whenever cash flow becomes positive. With the assumption that a fixed value of 40 years is used for vehicle lifespan, the net profit measures the cash flow at year 40 and may be either positive or negative, depending on whether the vehicle breaks even.

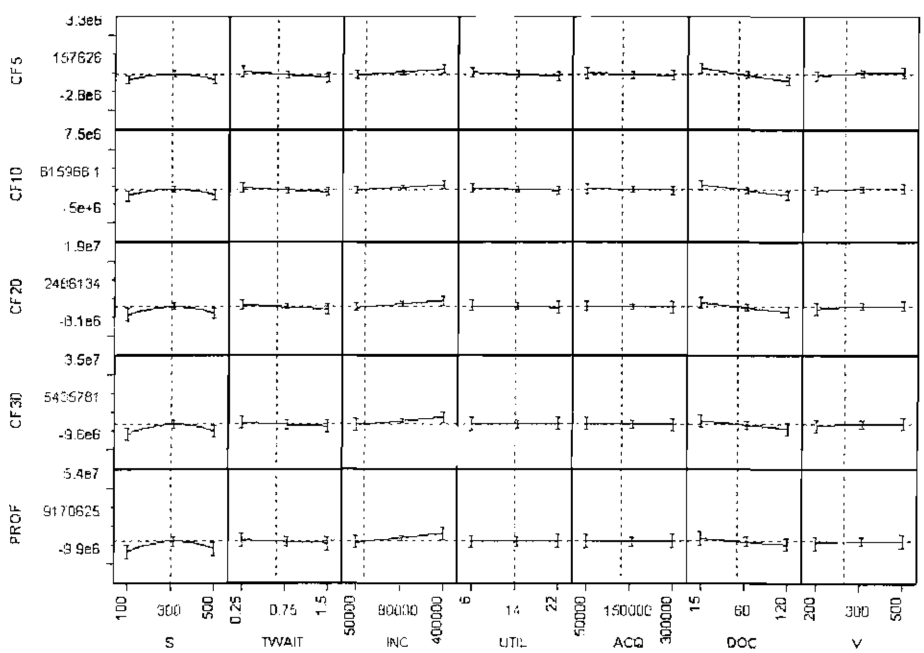
Table 3: Metrics of Interest

Description	Symbol	Unit
Block speed	VBLOCK	mph
Doorstep-Destination Time	TIME	hour
Vehicle Time Saving Index	VTSI	N/D
Cashflow at year 5	CF5	year
Cashflow at year 10	CF5	$
Cashflow at year 20	CF20	$
Cashflow at year 30	CF30	$
Net Profit	PROF	$

Visualization of the response surfaces is achieved through prediction profilers (Figure 11). The most outstanding observation from the prediction profilers is that a travel distance of 300 nm appears to be the most favorable travel distance for PAV concepts in terms of cash flows. The reasoning behind this observation is that for short distances, the economic benefits of travel time-savings by PAVs are not materialized.



a) Performance Metrics



b) Economic Metrics

Figure 11: Parametric Results: Prediction Profilers on Performance and Economic Metrics

Meanwhile, for long distances, the high cruise speed of commercial airliners overcasts the significance of value of time saved by utilizing PAVs. This is further discussed in the later section for modeling of existing PAV environment. Also, as expected, Figure 11 a) clearly shows that improvement in vehicle cruise speed has a positive impact on VTSI, which is the only factor that dictates the receipts in the cumulative cash flow. VTSI is also significantly and negatively related to the wait time at portals. Subsequently, a higher cruise speed and a lower wait time will yield a higher cumulative cash flow at every point of time within the life cycle of the vehicle, as shown in Figure 11 b).

To illustrate the utility of this RSM approach, an example using the contour profiler is shown in Figure 12 by plotting vehicle cruise speed (V) against wait time at portals (TWAIT). The two constraints imposed are the requirements to break-even in 5 and 10 years respectively. The contour lines ranging from 2 to 4.5 are the D-D time contour lines. The other mission factors are assigned values as shown in the table. For a given break-even point, say 5 years, the optimal cruise speed and wait time is desired such that a D-D time of 3.5 hours can be achieved. This is now an easy task as the tool provides slider bars that can be used to traverse along the plot until feasible space is found. For this particular example, the optimal tradeoff solution is when V lies at 286 mph and TWAIT at 0.96 hour or 57.6 minutes (marked by an X in the plot). Another practical example could be a user locating feasible space by trading off between vehicle speed and cost required to achieve break-even in year 10 for assigned values of his/her household income, utilization, and travel distance.

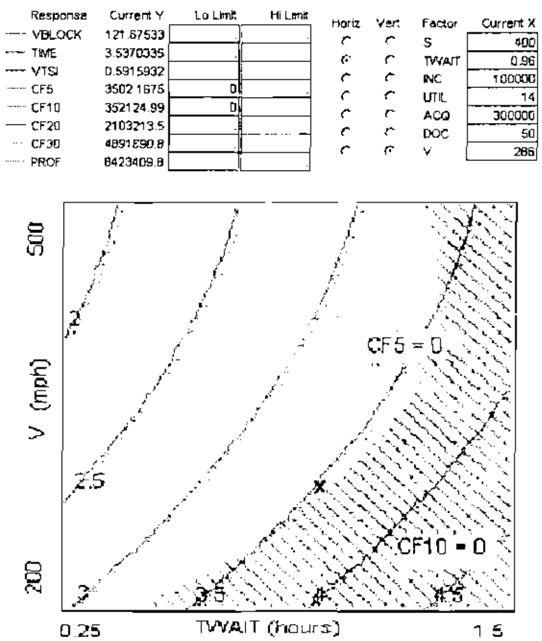


Figure 12: Contour Profiler

Many other scenarios can be generated from these prediction and contour profilers. These two tools present the analysis space as a parameterized tradeoff environment that is visibly comprehensible and easily manipulated. This promotes intelligent decision making by allowing the user to create scenarios where he or she can clearly visualize the impact of the parameters on the responses of interest and locate feasible space if any exists.

SCENARIO MODELING (USING TASK 1)

The parameterized PAV environment produced in Task 1 allows the modeling of scenarios that are of interest to the following four parties/audiences: individual users, business entities, policymakers, and NASA. These scenarios are the first attempt at answering common yet vital questions that these four parties would have regarding the possibility, benefits, and risks of PAV operations as shown in Figure 13. Eventual integration of the Benefits Visualization Tool and the RSEs into the overall PAV environment that includes system dynamics and simulations will hopefully answer the remaining time-variant and less predictable questions that the microscopic model cannot.

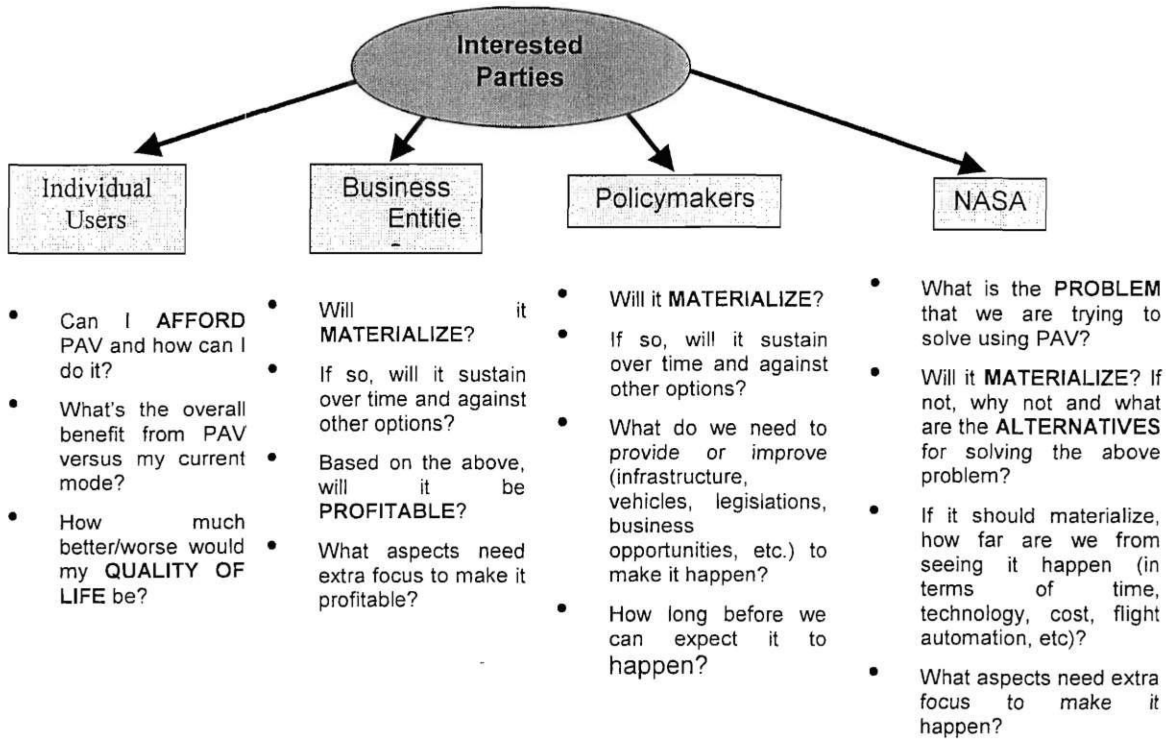
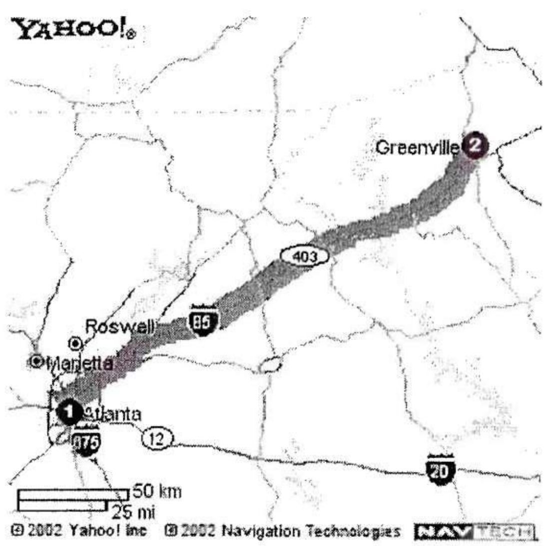


Figure 13: Common Questions Regarding Possibility, Benefits, and Risks of PAV Operations

Emphasizing on non-"time-variant" (i.e. model behaves independent of time without feedback) computations, selected scenarios of interests are modeled.



SCENARIO 1: John Doe (Individual User)

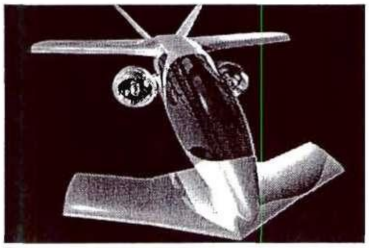
TIME: Year 2015
LOCATION: Atlanta, GA
PROFESSION: G.E. Gas Turbine Design Engineer
ANNUAL INCOME: $70,000
SITUATION: Recently transferred from G.E. Headquarter in Atlanta to G.E. Gas Turbine in Greenville, SC (~ 150 nm away)
OPTIONS:

i. Move family to Greenville
ii. Move to Greenville, visits family in Atlanta every weekend
iii. Commute from Atlanta to Greenville every day

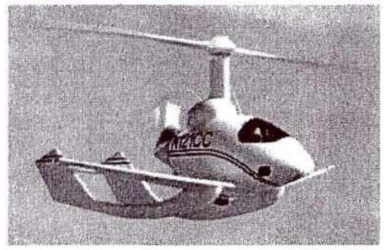
OBSERVATIONS:

i. Option iii seems appealing, but can John Doe **AFFORD** it?
ii. John Doe would need to commute to work 5 days a week and would use the PAV for leisure during one day of the weekends, hence totaling 12 trips per week.

Current most desirable/suitable PAV selections:



VEHICLE A
•Vehicle Price = $100,000
• Cruise Speed = 320 mph
•DOC = $55/hour



VEHICLE B
•Vehicle Price = $130,000
• Cruise Speed = 280 mph
•DOC = $45/hour

RSEs obtained in Task 1 are used to analyze these two PAV selections for John Doe's situation.

RESULTS:

	Vehicle A	Vehicle B	% Difference Relative to Vehicle A
Vehicle Price	$100,000	$130,000	**30.00%**
DOC/hr	$55	$45	**-18.18%**
Cruise Speed (mph)	320	280	**- 12.50%**
Travel Time (hours)	2.111	2.206	**4.52%**
Cash Flow at Year 5	-$71,935	-$29,313	**59.25%**
Cash Flow at Year 10	$1,004	$90,842	**8947.58%**
Cash Flow at Year 20	$587,585	$788,824	**34.25%**

Table 4: Analysis of Vehicle A and Vehicle B for Scenario 1

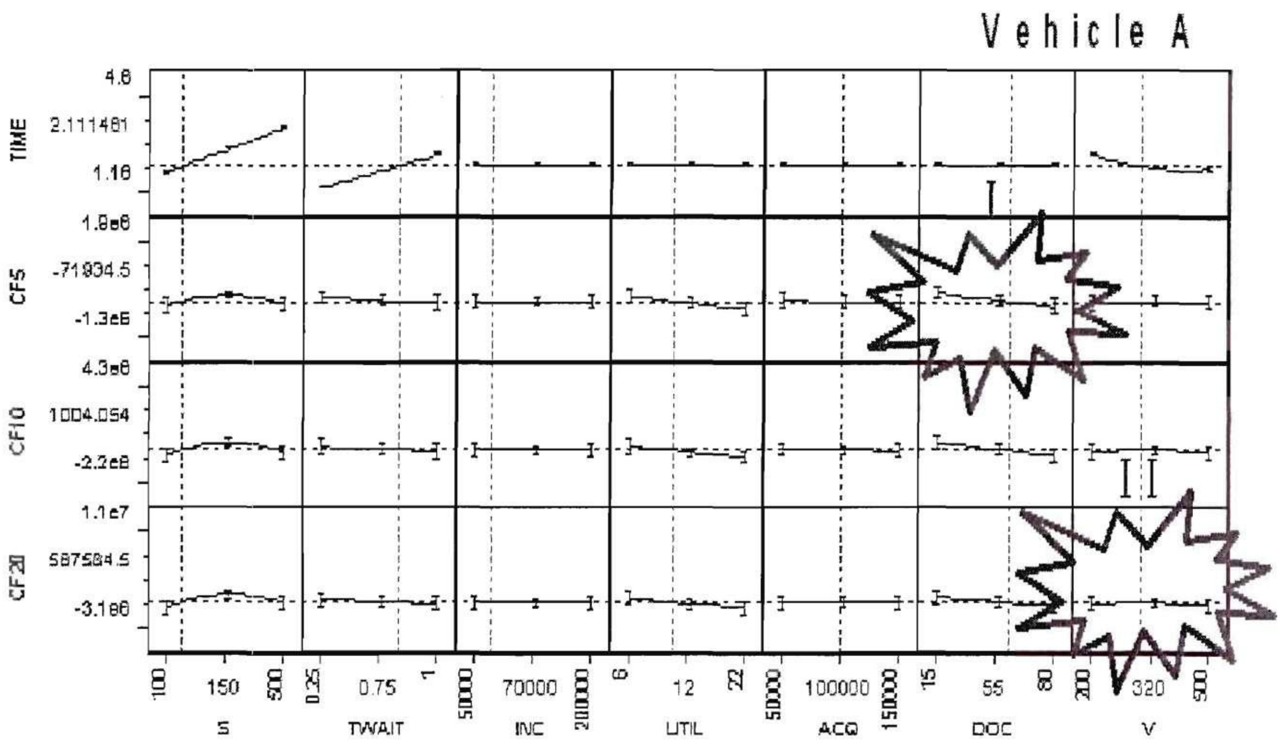


Figure 14: Prediction Profiler for Vehicle A of Scenario 1

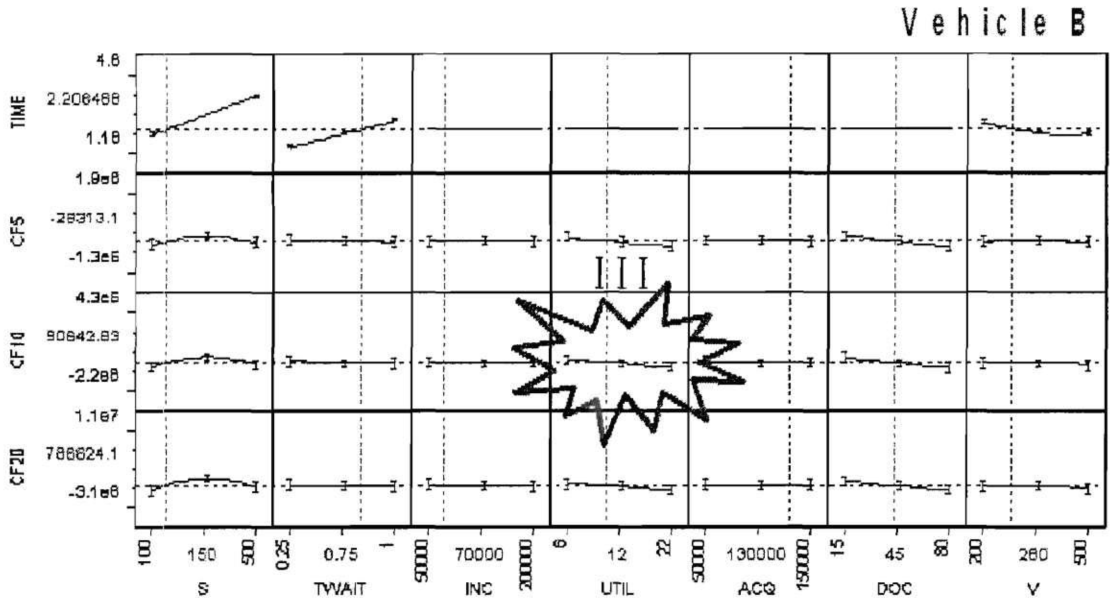
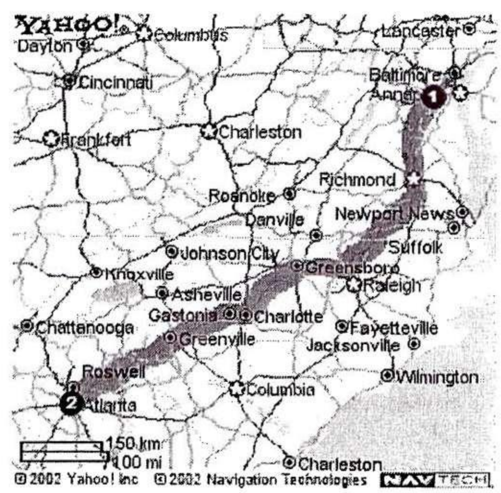


Figure 15: Prediction Profiler for Vehicle B of Scenario 1

CONCLUSIONS:

1. Vehicle B yields a higher cash flow than Vehicle A at all instances, despite costing $40,000 more and 10 mph slower (See Table).
2. For shorter distances, DOC has the biggest influence on the cash flow (steeper slope, See **I**) whereas Cruise Speed only has a small impact on cash flow (more gradual slope, See **II**)
3. For low income and low cruise speed, increasing utilization will decrease cash flows due to high DOC (See **III**)



SCENARIO 2: John Doe Sr. (Individual User)

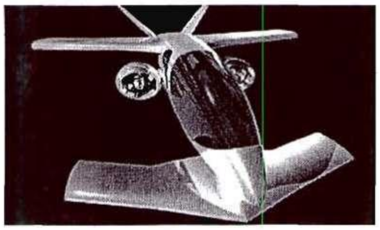
TIME: Year 2015
LOCATION: Atlanta, GA
PROFESSION: G.E. Gas Turbine Design Engineer
ANNUAL INCOME: $180,000
SITUATION: Recently required to work intensively with Congress representatives over gas turbine technology transfer to South Korea
OPTIONS:

i. Move family to Washington, DC
ii. Move to Washington, visits family in Atlanta once a month
iii. Commute from Atlanta to Washington every day

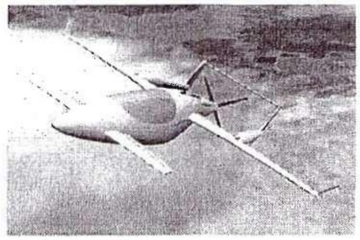
OBSERVATIONS:

i. Option iii seems appealing, is it worth the time, money, and effort?
ii. John Doe would need to commute to Washington (~ 480 nm away) 3 days a week and would assumingly use the PAV for leisure for one day, hence totaling 8 trips per week.

Current most desirable/suitable PAV selections:



VEHICLE A
- Vehicle Price = $100,000
- Cruise Speed = 320 mph
- DOC = $55/hour



VEHICLE C
- Vehicle Price = $150,000
- Cruise Speed = 440 mph
- DOC = $70/hour

RSEs obtained in Task 1 are used to analyze these two PAV selections for John Doe Sr. situation.

RESULTS:

	Vehicle A	Vehicle C	% Difference Relative to Vehicle A
Vehicle Price	$100,000	$150,000	**50.00%**
DOC/hr	$55	$70	**- 27.27%**
Cruise Speed (mph)	320	440	**37.50%**
Travel Time (hours)	3.357	2.842	**-15.35%**
Cash Flow at Year 5	$89,952	$72,585	**-19.31%**
Cash Flow at Year 10	$363,435	$372247	**2.42%**
Cash Flow at Year 20	$1,482,264	$1,678,700	**13.25%**

Table 5: Analysis of Vehicle A and Vehicle C of Scenario 2

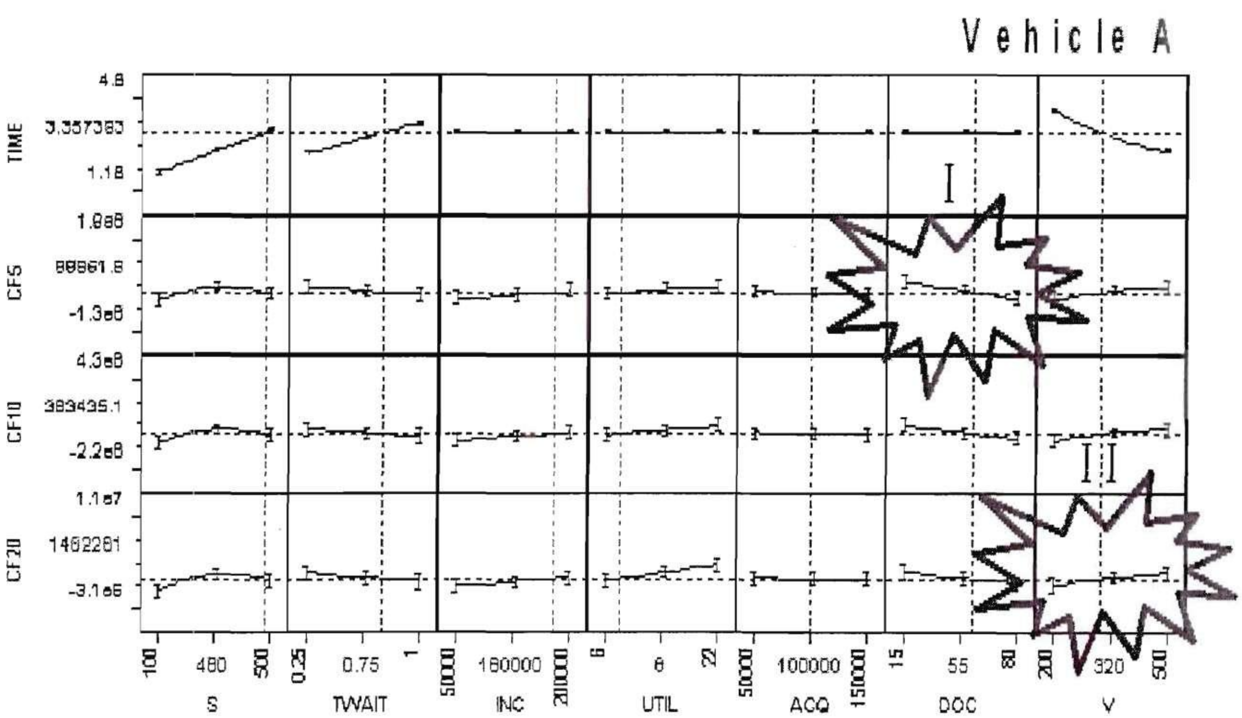


Figure 16: Prediction Profiler for Vehicle A of Scenario 2

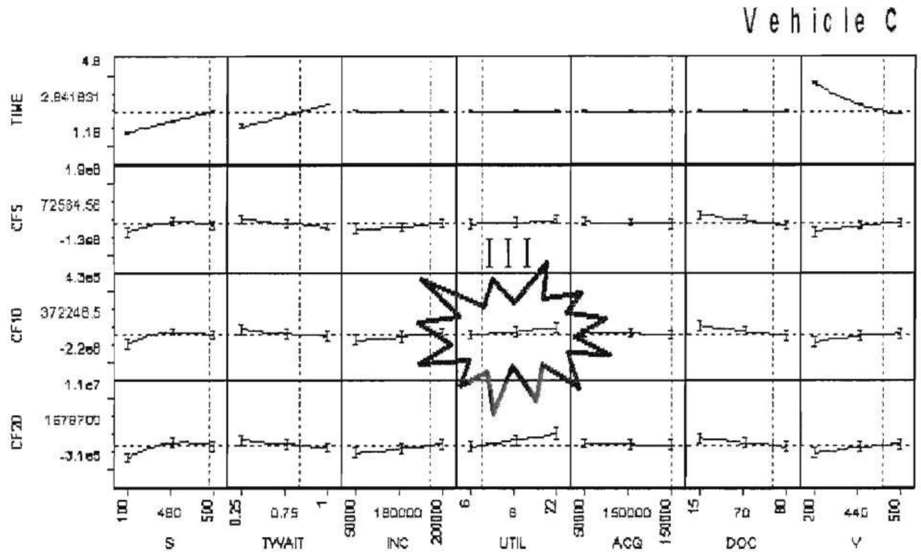


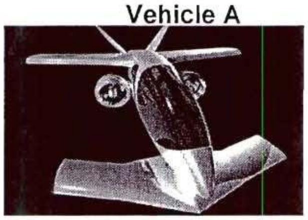
Figure 17: Prediction Profiler for Vehicle C of Scenario 2

CONCLUSIONS:

1. Vehicle C yields a lower cash flow at year 5 but increased for periods after that
2. Vehicle C costs \$50,000 more and \$25 more to operate, but is 120 mph faster (travel time reduced by 31 minutes).
3. For longer distances, both DOC and Cruise Speed impacts the cash flow significantly (See **I** & **II**)
4. For high income, increasing utilization will significantly increase cash flows due to large value of time saved (See **III**), which benefits John Doe Sr. in any case his trips becomes more frequent

<u>SCENARIO 3: Market Analysis Tool (Business Entities)</u>

Vehicle A

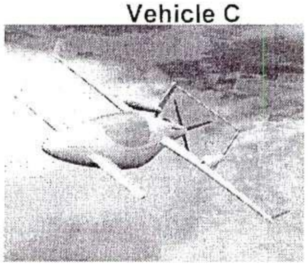


- Vehicle A is a mid-speed PAV offered at a low price. The additional booster in the propulsion unit improves the average cruise speed at the expense of a slightly higher DOC, yet without increasing the price too much.
- Targeted markets are consumers with average income who travels frequent mid-distance trips (~300 nm), where both speed and DOC are significant in determining viability

Vehicle B

- Vehicle B is a low-speed and low cost autogyro PAV. The price is slightly higher largely due to the advanced avionics that provide the high handling qualities and controls.
- Targeted markets are consumers with average income who travels frequent short-distance trips (100 - 250 nm), where DOC becomes the dominating determinant for viability.

Vehicle C



- Vehicle C is an advanced high-speed PAV. The price is 50% higher than the average PAV, largely due to the advanced propulsion system and avionics that propels the vehicle at an impressive 440 mph cruise speed. Inevitably, DOC is also higher due to the increased cruise speed.
- Targeted markets are consumers with high income who travels long-distance trips (350 - 500 nm), where travel time becomes just

Vehicle manufacturers may utilize the benefits visualization tool and RSEs similarly to Scenarios 1 and 2, by creating scenarios to match Personal Air Vehicles to collective group of consumers. Using Vehicles A, B, and C from the previous scenarios, the vehicle-consumer matches shown above are made:

SCENARIO 4: NASA & Policymakers

The benefits visualization tool and RSEs provides NASA and policymakers with the following information:

1. Identify worst-case and best-case operating environments within the metamodel boundaries.
2. Identify factors that impact the operating environment in terms of **block speed** and **cash flows**, where block speed serves as the unified metric for comparing D-D time for different travel distances simultaneously since travel time by itself is inconsistent for comparing different travel distances.
3. Outline the realistic interpretation of the factors obtained above.
4. Create a PAV environment that benefits the society at large, by realistically emphasizing on the average commuters' affordability.

Worst-Case Scenario 1:

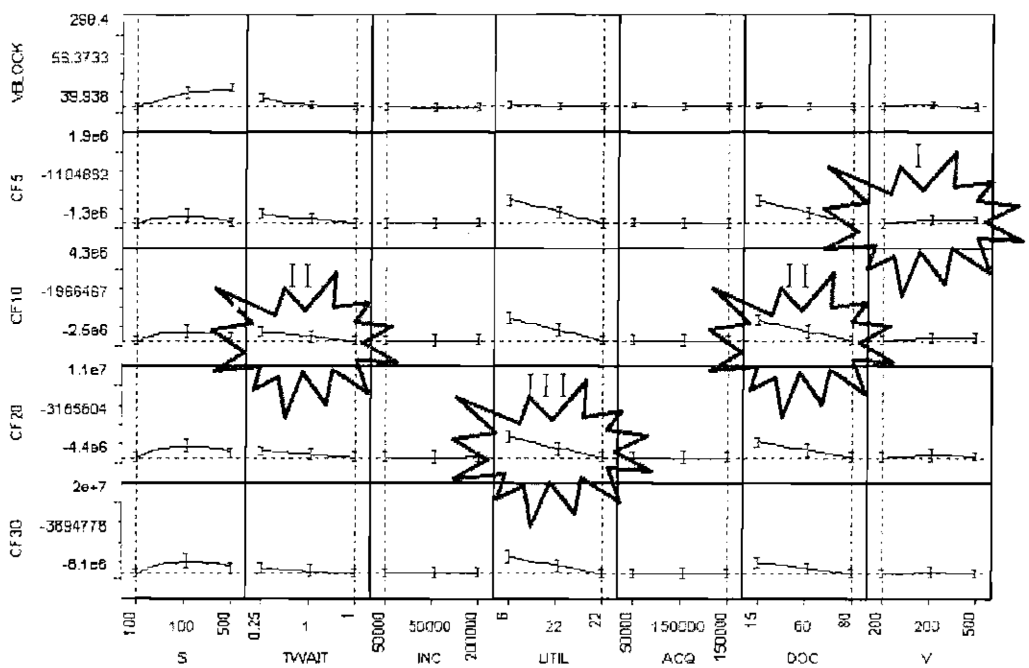


Figure 18: Prediction Profiler for Worst-Case Scenario 1

OBSERVATIONS:

i. Within the metamodel boundaries, the worst-case operating condition for a PAV is when the *impact of high vehicle operating cost overshadows the benefits of D-D time reduction*, i.e. low speed, long wait time, and high DOC.

ii. For travel distance of **100 nm**, the advantage of a PAV in reducing D-D time (mostly during the air leg) becomes moot when the air leg is short. Hence, cruise speed has little impact on the cash flows (See **I**).

iii. DOC and wait time at portal are the two most significant factors under this worst-case operating condition (See **II**).

iv. Under this operating condition, vehicle acquisition price and user income has little effect on the cash flows.

v. The worst-case scenario is strongly compounded when utilization increases (See **III**).

Worst-Case Scenario 2:

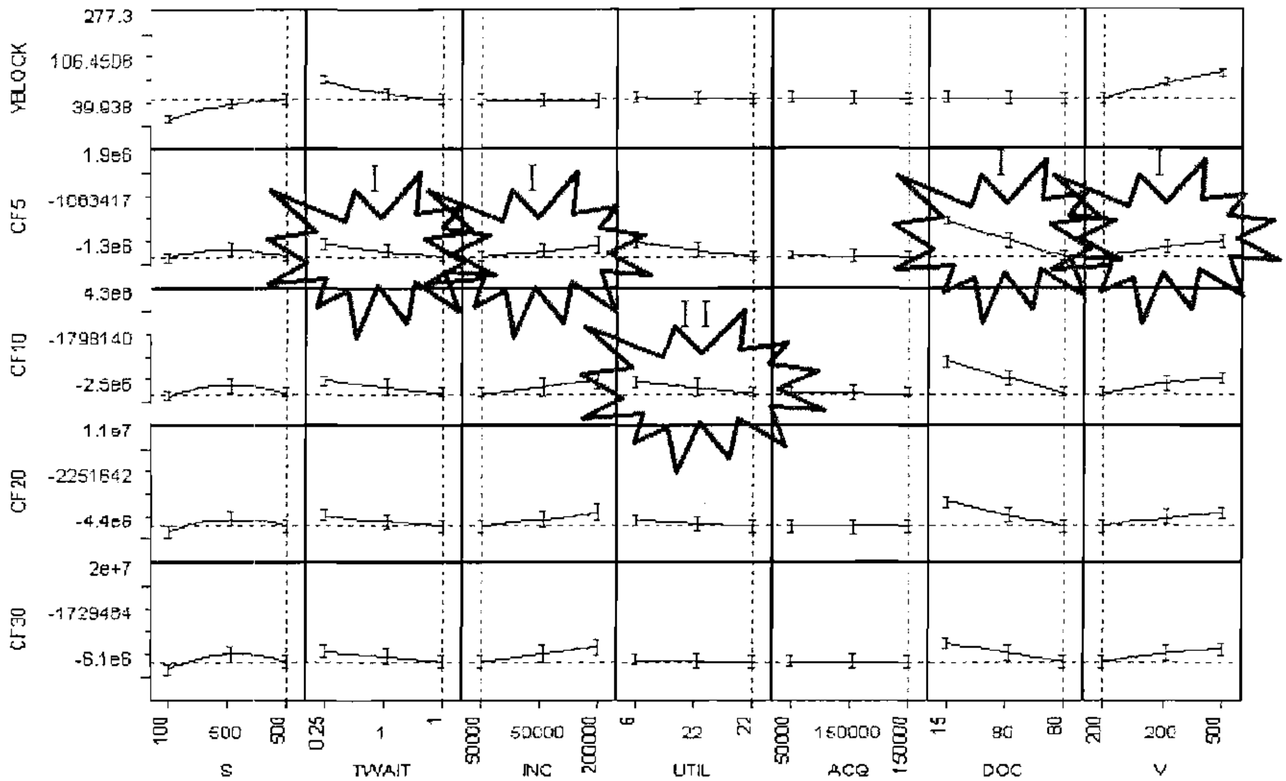


Figure 19: Prediction Profile of Worst-Case Scenario 2

OBSERVATIONS:

i. Within the metamodel boundaries, the worst-case operating condition for a PAV is when the *impact of high vehicle operating cost overshadows the benefits of D-D time reduction*, i.e. low speed, long wait time, and high DOC.

ii. For travel distance of **500 nm**, the high DOC compounds the unfavorable value of time savings due to the low income and low speed.

iii. DOC, wait time at portal, user income, and vehicle cruise speed are the most significant factors under this worst-case operating condition (See **I**).

iv. Under this operating condition, vehicle acquisition price has little effect on the cash flows.

v. During the first 10 years, the worst-case scenario is compounded when utilization increases (See **II**) but the impact reduces after 10 years.

vi. NOTE that *Worst-Case Scenario 1* is much worse off than *Worst-Case Scenario 2* in terms of block speed (56 mph as compared to 106 mph) although cash flows are not significantly different from one another.

CONCLUSION:
PAV is NOT a good alternative for very short distances and extremely long distances.

Best-Case Scenario:

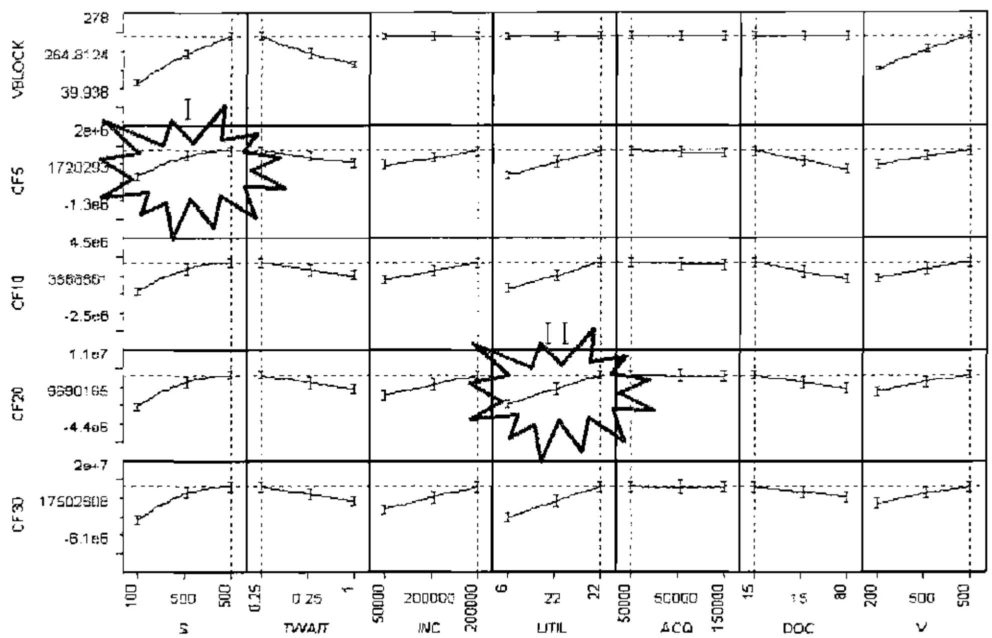


Figure 20: Prediction Profile of Best-Case Scenario

OBSERVATIONS:

i. Within the metamodel boundaries, the best-case operating condition for a PAV operating environment is when *the low cost of the vehicle operations* compounds the *D-D time reduction,* i.e. high speed, low DOC, and short wait time.

ii. Under this operating condition, it is most favorable to take long distance trips since value of time saved will increase (See **I**).

iii. All factors except for acquisition price have significant impacts on the cash flows.

iv. The best-case scenario is strongly compounded when utilization is increased (See **II**).

Realistic Interpretation of Significant Factors:

The 7 variables in the RSEs can be categorized into uncertainties and user-determined factors, as shown in Table 6 below. The uncertainties are present simply because the RSE is a metamodel of a futuristic PAV environment that is based solely on assumptions and intuitions of the vehicle and infrastructure development. Based on the worst-case and best-case scenarios as well as the equations for block speed and cash flows computations, it is determined that travel distance heavily dictates the impacts and relationships of the remaining 6 factors. Thus the first step before using the prediction profilers for visualization is to determine the travel distance. It is also determined that every other factor except vehicle acquisition price significantly and uniquely impacts the block speed and cash flows for different combination of factors.

Economics Uncertainties	Direct Operating Cost (DOC) Acquisition Price (ACQ)
Technology Uncertainties	Vehicle Speed (V)
Infrastructure Uncertainties	Wait Time at Portal (TWAIT)
User-Determined Factors	Travel Distance (S) User Income (INC) Utilization (UTIL)

Table 6: Categorization of RSE Design Variables

Subsequently, a PAV environment is created by varying three main uncertainties (TWAIT, DOC, V) while keeping the remaining factors fixed (ACQ = \$150,000, S = 400 nm, INC = \$50,000, UTIL = 12 trips/week). Initial values for the uncertainties are 0.75 hour, \$70/hour, and 320 mph respectively. The main objective of this fabricated environment is to investigate the affordability of PAV to the average salary individual. For simplicity, breakeven at year 5 (CF5 = 0) is adopted as the measure of merits. The results are shown in Figure 21 below:

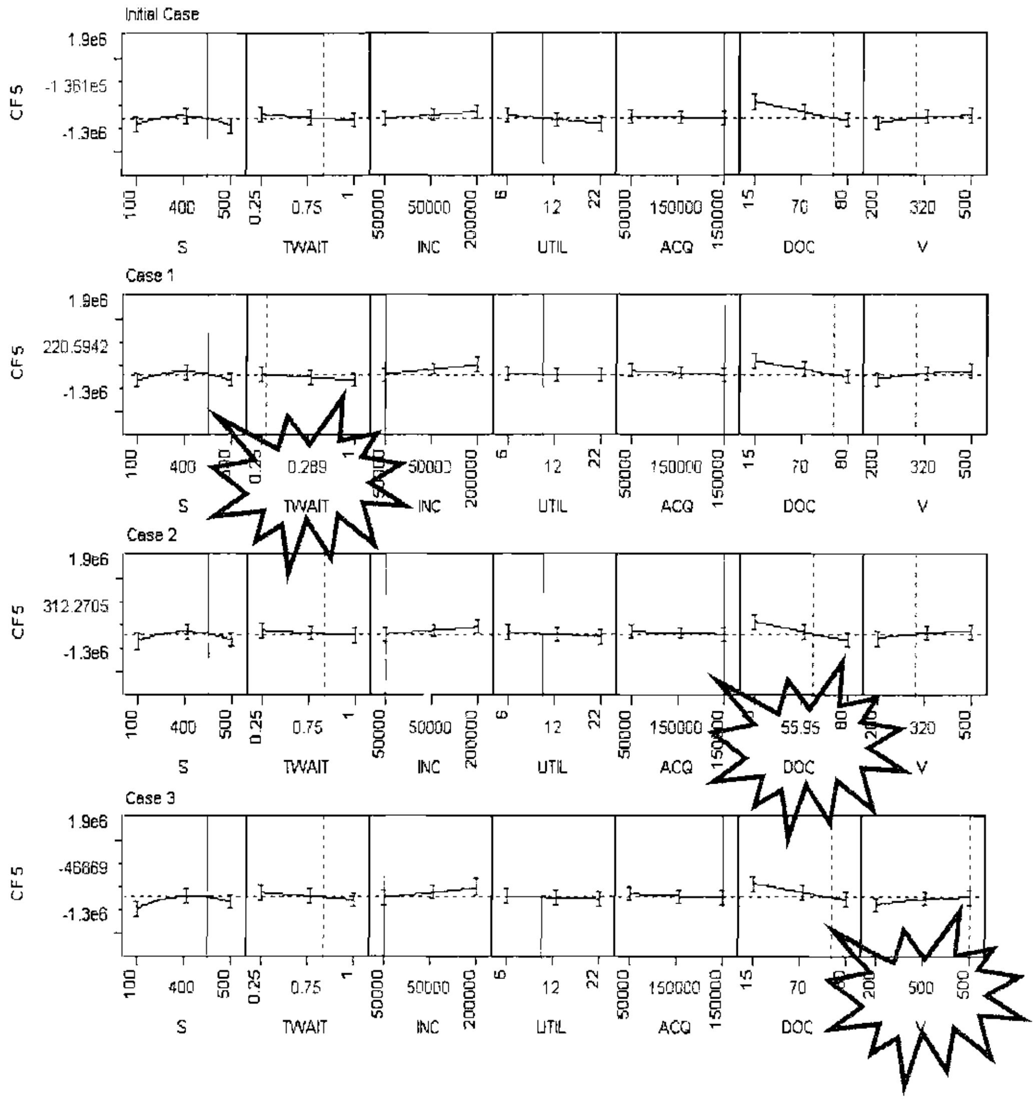


Figure 21: Initial Case and Tradeoff Cases

For the initial case where initial values are used for the uncertainties, user yields a cash flow at year 5 (CF5) of -\$136,100 (i.e. breakeven unachievable).

For Case 1, TWAIT is varied while keeping DOC and V fixed at the initial values. Breakeven at year 5 is achieved when TWAIT is lowered from 0.75 hour (45 mins) to 0.289 hour (17.5 mins), a reduction of 27.5 minutes (57.5%). Realistically, this is an extremely difficult task as the PAV facility traffic handling rate is very constrained by cost, technology, and human factor.

For Case 2, DOC is varied while keeping TWAIT and V fixed at the initial values. Breakeven at year 5 is achieved when DOC is lowered from \$70/hour to \$55.95/hour, a reduction of ~\$14/hour (20%). Realistically, this too is a very difficult task that requires a compromise between technologies, performance, and most importantly, time.

For Case 3, V is varied while keeping TWAIT and DOC fixed at the initial values. Breakeven at year 5 cannot be achieved even when vehicle speed is increased to the maximum metamodel boundary of 500 mph. Furthermore, speed improvement is a very expensive RDT&E process, which will in turn affect cost factors significantly.

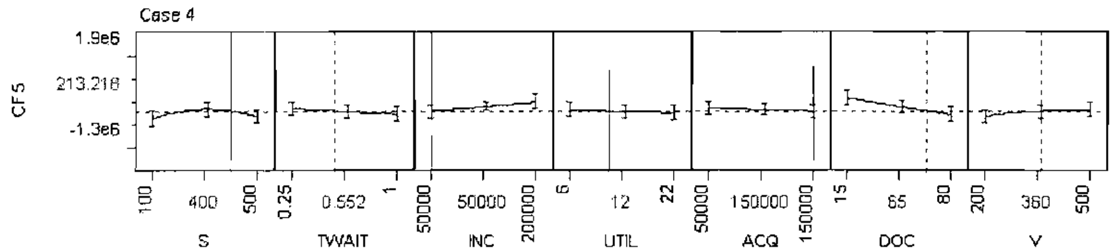


Figure 22: Feasible and Viable PAV Environment

For Case 4 (Figure 22), all three uncertainties are varied to a level that is realistically achievable and within the metamodel boundaries. Instead of requiring an alarming reduction of 27.5 minutes in TWAIT, only 12 minutes is required. Simultaneously, a $5/hour reduction in DOC (7%) and 40 mph speed improvement (12.5%) are required. Discovery of new vehicle propulsion technologies that yields high-speed yet cost-efficient vehicles will introduce speed improvement and reduction in DOC at a manageable increase in RDT&E cost for acquiring the technology. Subsequent improvements in infrastructure technologies and most importantly, traffic management and controls will result in faster traffic handling and shorter wait time. Hence, the target of breakeven at year 5 can be achieved.

This tradeoff example merely shows the capability of the prediction profiler in creating a visually comprehensible and easily manipulated trade study for any form and specification of PAV operating environment, emphasizing either on affordability, practicality, or sheer creativity.

TASK 3: EXISTING PAV CONCEPT ANALYSIS ENVIRONMENT

The primary objective of this implementation of the benefits visualization tool is to compare the feasibility and viability of several existing potential PAV options. Subsequently, a gap analysis can be performed to identify required technology infusions. Unlike the previous task, this task seeks to model a current PAV environment based on these existing PAV options, some of which are currently in service. However, only 6 out of the 16 PAV options have sufficient data available for the modeling, as shown below:

CLASS	*MODE*	*SPEED*	*VEHICLE NAME*
VTOL	Single	Slow	Robinson R-44
		Fast	-
	Dual	Slow	Boeing DART*
		Fast	-
SSTOL	Single	Slow	Groen Hawk 4
		Fast	Cartercopter Gyroplane
	Dual	Slow	-
		Fast	-
STOL	Single	Slow	-
		Fast	-
	Dual	Slow	-
		Fast	-
CTOL	Single	Slow	Lancair Columbia 400
		Fast	Eclipse 500
	Dual	Slow	-
		Fast	-

* Conceptual Design Only

Figure 23: Existing Potential PAV Options

Performance and economic data on these vehicles are researched and are entered into the vehicle database of the benefits visualization tool. These data are used for performance and economics computations described earlier. The primary measures of merit are D-D travel time-savings and net present value of utilizing the PAV option relative to the baseline transportation mode, represented by adjusted cumulative cash flow analysis. A set of assumptions accompany the computation of these two measures of merit:

1. All scenarios are modeled based on current existing vehicles, hence, employing current performance, technology, and economics assumptions.
2. For illustrative purposes, only 2 parameters are selected for sensitivity analysis while all others are kept fixed. These two parameters are household income and travel distance.
3. Household income is varied for two values: $200,000 and $350,000. These are realistic values based on tradeoffs between performance and costs of current technology level vehicles.
4. 5 scenarios are created for each household income level by varying travel distance from 100 nm to 500 nm in steps of 100 nm. This range is selected based on typical design and mission range of the existing potential PAV options.
5. Assumed values for mission and economics options (as discussed in Interface) are as follows:

Mission Options	*Values*
Trips Made Per Week (6-22)	14 trips/week
Number of 'PAV-pooling' passengers (max 4)	2 passengers
Vehicle Economics Options	*Values*
Downpayment (as fraction of vehicle acq. cost)	15.0%
Loan Interest Rate (Annual)	9.0%
Use Recommended Loan Period? If yes, type 'y' in box, else, enter loan period below.	y
Loan Period	12 years
Predicted Lifespan of Vehicle (50 years max.)	40 years
User's Economics Options	*Values*
Predicted income change per year in first 5 years (+/-) is :	5.0%
Predicted income change per year in following 5 years (+/-) is :	5.0%
Predicted income change per year in following 5 years (+/-) is :	5.0%
Other Economics Variables	*Values*
Annual percentage allocation for transporation	15.0%
Annual Inflation Rate	3.7%
Annual Nominal Interest Rate	7.0%
Annual Real Interest Rate	3.2%

Figure 24: Mission and Economics Assumptions

The net present values (NPV) of utilizing these 6 potential PAV options at the end of vehicle lifespan are obtained using the benefits visualization tool. Three observations can be made from the results shown below. First, it can be determined if the vehicle breaks even for a given travel distance. This is portrayed by the shaded cells in Figure 25 and Figure 26. Second, it can be shown which travel distance is most appropriate for PAV operations. Third, the net profit of the vehicles can be compared to identify which vehicle is most viable and/or profitable.

	40-Years Net Present Value for Income = $200,000 ($ Million)				
	100	200	300	400	500
R-44	-2.038	-1.094	0.263	-2.662	-4.055
DART	-0.591	0.008	2.305	0.319	-1.293
Hawk 4	-4.439	-4.117	-2.229	-4.621	-6.471
Cartercopter	-4.882	-2.702	0.599	-0.381	-0.988
Lancair	-2.513	-0.995	1.509	-0.269	-1.674
Eclipse 500	-4.350	-0.895	2.560	1.733	1.280

Figure 25: NPV of Vehicles for Household income = $200,000

	40-Years Net Present Value for Income = $350,000 ($ Million)				
	100	200	300	400	500
R-44	-1.968	-0.008	2.674	-2.098	-3.984
DART	-0.591	3.613	7.818	4.570	2.179
Hawk 4	-4.037	-3.164	0.451	-3.387	-6.070
Cartercopter	-3.911	-0.091	5.691	4.021	3.208
Lancair	-2.050	0.786	5.346	2.453	0.418
Eclipse 500	-3.712	2.295	8.301	6.855	6.266

Figure 26: NPV of Vehicles for Household income = $350,000

The results above verify that household income is a critical factor in determining whether or not a PAV is viable. Less than one third of the combinations of vehicle and travel distance break even when the user makes $200,000 annually as compared to more than a half when the user makes $350,000. This is as expected since household income is a key player behind the value of time concept. However, the primary finding in these results is that PAV operations are most viable at 300 nm travel distance while worst at the extremely low travel distance of 100 nm. The reasoning behind this observation is that for low distances, the economic benefits of travel time-savings by PAVs are not materialized. Meanwhile, for long distances, the high cruise speed of commercial airlines outweighs the delay time penalty at airports such that value of time saved by PAV becomes less significant. This observation is more apparent by plotting the adjusted cumulative cash flow of different travel distances for the Eclipse 500. The arrow in Figure 27 shows the cash flow trends from travel distance of 100 nm to 500 nm. Clearly, travel distance of 300 nm yields the highest adjusted cumulative cash flow for the Eclipse 500.

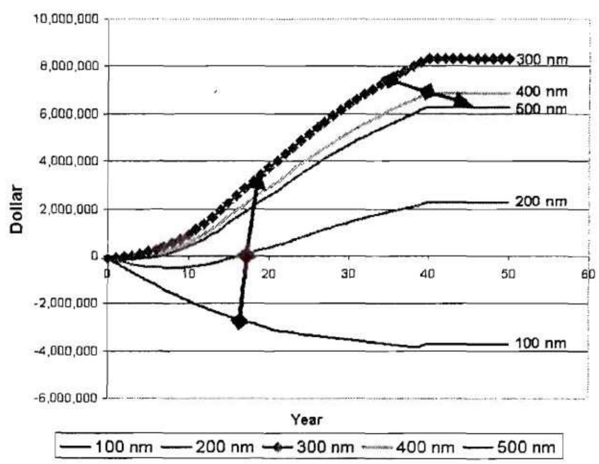


Figure 27: Adjusted Cumulative Cash Flow for Eclipse 500 for Varying Travel Distances (Household income = $350,000)

From the cash flow analysis for all vehicles, the Eclipse 500 is the most viable PAV option for both income levels, followed by the Boeing DART and the Lancair Columbia 400. One of the apparent observations made is that both the Eclipse and Lancair are CTOL general aviation aircraft. The Boeing DART, despite being a dual mode, high speed, light vehicle, is merely at its concept development stage. None of the VTOL or SSTOL vehicles currently in service fared well in the analysis. Despite the many advantages of VTOL concept, existing technologies had not made it possible for these vehicles to operate fast and cheap enough to compete with the much faster general aviation aircrafts. Having identified vehicle cruise speed and cost as two areas that require technology pursuit, a sensitivity analysis is performed on the VTOL R-44 light helicopter. A technology complexity factor is included in the cash flow analysis such that technology infusion allows improvements of 15%, 30%, and 45% on cruise speed (V), acquisition cost (ACQ) and direct operating cost (DOC). The assumptions made are similar to those given in Figure 24 and based on a $200,000 annual household income level.

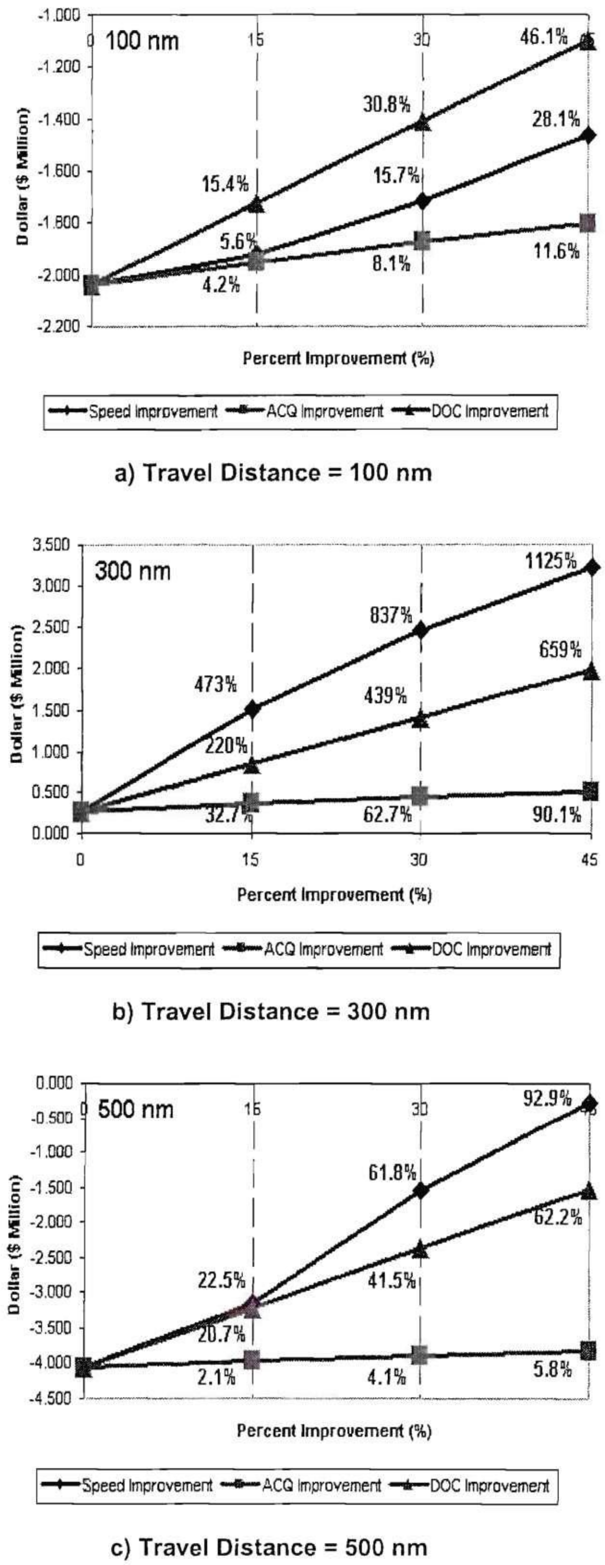


Figure 28: Net Profit of R-44 in Year 40 with Varying Complexity Factors

Two main observations are made based on the technology sensitivity analysis. Firstly, for a short distance trip (100 nm), reduction in DOC yields the greatest increase in net profit whereas for a long distance trip (500 nm), increase in cruise speed yields the greatest increase in net profit. This can be explained by the fact that vehicle speed improvement will not significantly benefit the viability of the PAV option for short distance traveling since the air leg travel time is small compared to the ground leg travel time. Subsequently, reduction in DOC becomes the more pronounced factor in improving viability. Secondly, a reduction in the vehicle acquisition cost is least significant to improving vehicle viability. Hence, technologies that create fast and cost efficient vehicles at the expense of higher production cost are favorable in designing a viable PAV. From these observations, the new generation of PAV is anticipated to be a cost efficient vehicle that is relatively faster while possessing the advantages of VTOL capability.

Despite the analysis and observations made above, there is a clear recognition that major advancements in technology are needed to make PAVs affordable for large percentage of the populace (i.e. those who make less than $200,000). The identification of such technologies is the current prime directive of the NASA program that funded the research reported here.

Summary thoughts and Future Work

When modeling a future PAV operating environment, historical data on current transportation systems can only provide insights in specific and limited levels/steps of modeling. Hence, intuitive and practical thinking are essential in forecasting the futuristic environment to an acceptable level of fidelity and providing a useful tool to the sponsors of this research program. A few important issues arise as consequences of such thought processes. They are the definition and classification of mobility freedom created by PAV in the enhancement of the 'quality of life', the corresponding growth in PAV infrastructure and legislative development, and the socio-economic adjustment with the presence of PAV. Our intended future work will focus on such issues, initially from a very specific perspective, before generalizing the problem for commonality of the main objective of the research program.

Our PAV research to date has resulted in a general conclusion that the current crop of potential PAVs listed in Task 3 above (for example) are unaffordable and under-performing in the mission of providing a "kick-start" to an on-demand mobility environment. Neglecting the infrastructure and legislative issues momentarily, a PAV will become attractive to the general public only if it is affordable, that is, evaluation of ***benefits*** (travel time saved and quality of life improvement) exceeds that of ***costs*** (vehicle price and operating costs). Vehicle performance is largely dependent on technology and the costs of these technologies, whether in the hardware itself, or the RDT&E costs. And historically, the kiss of death for a vehicle program's success is low production rates for units of these air vehicles. Hence, the main focus in breaking this affordability barrier is to make options available and attractive to as many consumers as possible. However, enhancing PAV attractiveness by improving performance will simultaneously increase the costs, potentially creating a 'chicken and egg'-like situation to the problem. This is indeed a challenge.

On the closer horizon, business concept air vehicles has been identified as a possible initiative to tackle the above mention problem. The vehicles, termed Commercial On-Demand Air Vehicles (COAV) in this proposed research, comprise Business Concepts Small Aircraft Transportation Systems (SATS) and Air Vehicles (AV) in the form of fractional ownership air vehicles, air taxis, and charter air vehicles. Besides playing a key role in pushing the technology envelope such that PAVs can be made more available, affordable, reliable, and competitive with other transportation modes, COAV attempts to gradually introduce PAV as an alternative Doorstep-to-Destination (D-D) personal transportation solution to the general public. This is an important process as a sudden emergence of PAV may cause a cultural shock due to concerns such as safety, air worthiness, air traffic management, vehicle performance, and vehicle costs. This may lead to the absolute downfall of the PAV program especially with the emergence of other alternative transportation modes such as high-speed electric trains and Maglev trains.

Current work of COAV is still at its infancy stage. Essentially, there are three selections of COAVs: fractional ownership air vehicles, air taxis, and charter air vehicles, where air taxis and charter air vehicles are categorized together since their business concepts are analogous. Identification and comparison of these selections are shown in Figure 29. The overall goal of this research will be to develop a methodology employing system dynamics concepts and tools in conjunction with probabilistic design methods in order to study a family of potential COAV. The challenge of analyzing and designing revolutionary transportation concepts is that future transportation system infrastructure and market economics are also part of the equation, making the problem well suited for the field of system dynamics.

The architecture of the methodology is intended to be a system dynamics model that incorporates the transportation infrastructure system, alternative transportation modes, and market economics, wrapping around a vehicle sizing environment. Time-variant factors such as market demand and traffic capacity will provide feedback to the vehicle performance and economic characteristics as well as the business decisions made along the way. RSEs for potential COAVs such as the Robinson R-44, Bell 609, Groen Hawk 4, and a few other general aviation aircraft will be used as the vehicle characteristics sizing tool. The primary benefit metrics for these business concepts are the D-D travel time savings, investors' ROI, and market share. Applying these metrics, vehicle characteristics, and the systems dynamics model will enable the visualization of a COAV system benefits to guide the design space evolution through probabilistic sensitivity assessment. A successfully employed system dynamics environment for these business concepts not only will provide an improved understanding and confidence in introducing PAVs to the general public, but can be used to model the PAV system in a very similar manner. An overview of the methodology architecture is shown in Figure 30.

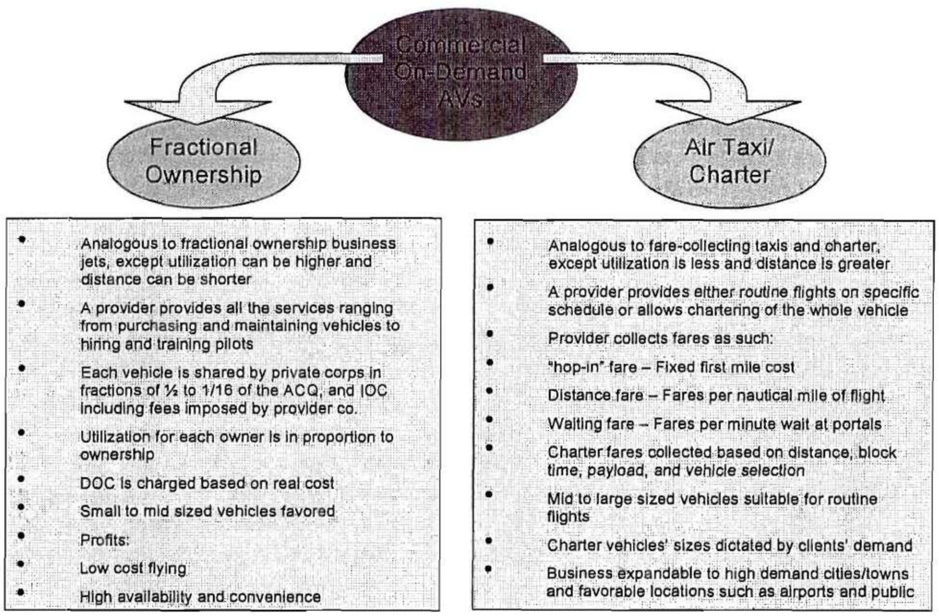


Figure 29: Comparisons of Fractional Ownership and Air Taxi/Charter Air Vehicles

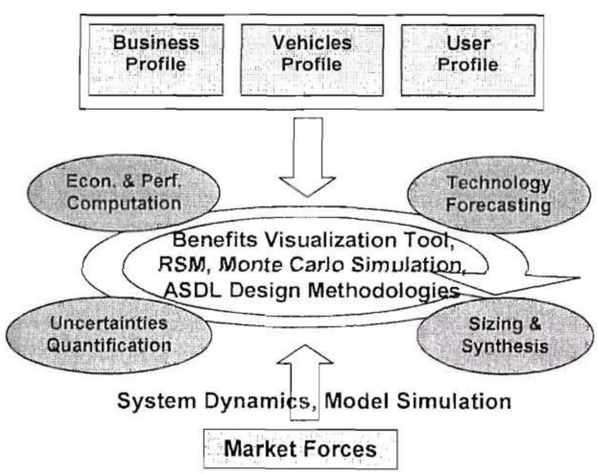


Figure 30: Overview of Proposed Business Air Vehicle Structure

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1.2. Wed-Based Implementation- An Environment for "Living System Studies"

In order to maximize the exposure of the PAV program and the usefulness of the methods developed, both internally towards management and externally towards the general public, ASDL was asked to create an interactive web site using the latest in JAVA technology. The site was to contain the core analysis tools developed as described above. This goal was successfully accomplished, and the web site has been delivered and demonstrated to the sponsor in electronic form and is available in updated form at http://www.asdl.gatech.edu/teams/pave. This section of the final report describes the construction and functionality of the site.

General Site Description

The structure of the web site was designed to be as simple as possible, with the minimum sections necessary to fulfill the requirements and with few complex objects such as *Flash* or other memory consuming items. This implementation allows users without the browser add-ons to directly use the tool without having to download the scripts, reduces the size of the site, and increases the download speed. The only script necessary to run the tool is Sun's *Java Virtual Machine.* This add-in is already included on most browsers, or available free if not. *Macromedia Dreamweaver 4.0* was chosen as the tool to develop the web site due to its good mixture of HTML and graphic oriented design capabilities and its ease of use.

It was deemed important to attract the users to visit the whole site, not just the Analysis Tool. Indeed, this tool as such is much more than just an analysis applet. It offers information about the current status of Personal Air Vehicles and the present developments being conducted. It should serve as a gateway to anyone interested in PAVs. A snapshot of the "catchy" home page is shown in Figure 31.

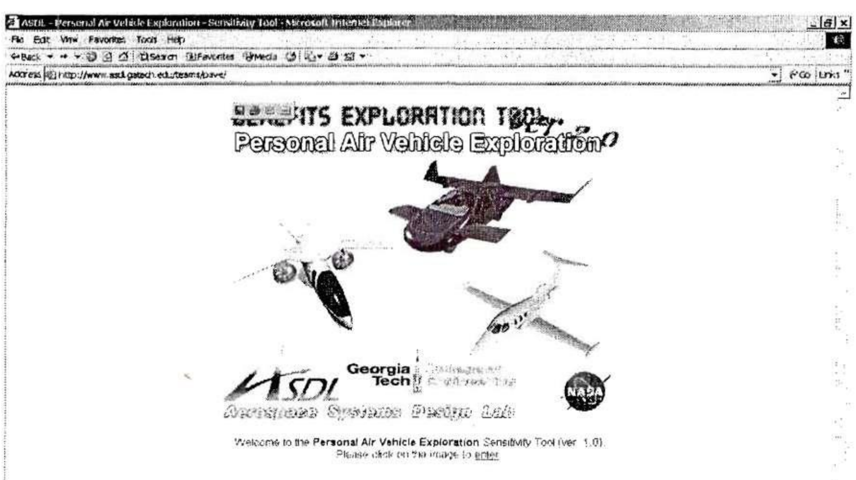


Figure 31: ASDL's PAVE Web Site Homepage

The navigation of the site is non-linear. The user can access every page from any other page, this allows for ease of navigation and simplicity of design. For all the pages, except the Intro, a frame layout was chosen. The layout is composed of a header, extending on the whole width of the page, a toolbar on the left and a main page on the right. With such a layout, the user does not have to re-load the title, images and buttons each time he or she changes section. In the future, the HTML toolbar can be replaced by a Flash Toolbar, Menu, or even be included as part of the JAVA applet.

JAVA APPLET

Java is an object-oriented language, allowing for different modules to be developed, tested individually and then added to a main tool. This results in a greater flexibility, and thus, there is the possibility to continuously expand and improve a particular tool. The applet was divided into different sections or tabs. These sections are meant to work in parallel and each one offers a different analysis or method of comparison. For example, the *Mission Tool* analyzes travel time for each vehicle. In particular, the user can easily compare the results of three different choices. The *Cash Flow* analyzes how much money the PAV costs and saves. On the other hand, in order to do so, it must also calculate how much time it saved when compared to the common options. Thus, there is some overlap between the tabs. However, from a usability point of view, the main calculated components were separated for simplicity. The user can switch between the sections and compare the different results separately.

Mission Analysis Applet Element

In the *Mission Analysis* applet the user can evaluate the time it would take for each individual vehicle option to complete a given mission. The mission variables that the user can change are the portal-to-portal distance – or range – and delay time at a portal. It is important to keep in mind that these values would vary between different vehicle types, such as VTOLs vs. CTOLs. The results can also be compared to today's traveling options, mainly the personal or rental car and the airplane. The Mission Analysis applet is already resulting in interesting analysis, such as evaluation of what range is viable to use a PAV or travel in a commercial jetliner.

The user can select up to three different main vehicle options. If the chosen vehicle is not a dual mode vehicle – i.e. cannot drive on the road – the user can choose between a rental car and a personal car to travel from the doorstep to the portal and from the portal to the destination. A snapshot of the applet displaying the *Mission Analysis* element is displayed in Figure 32.

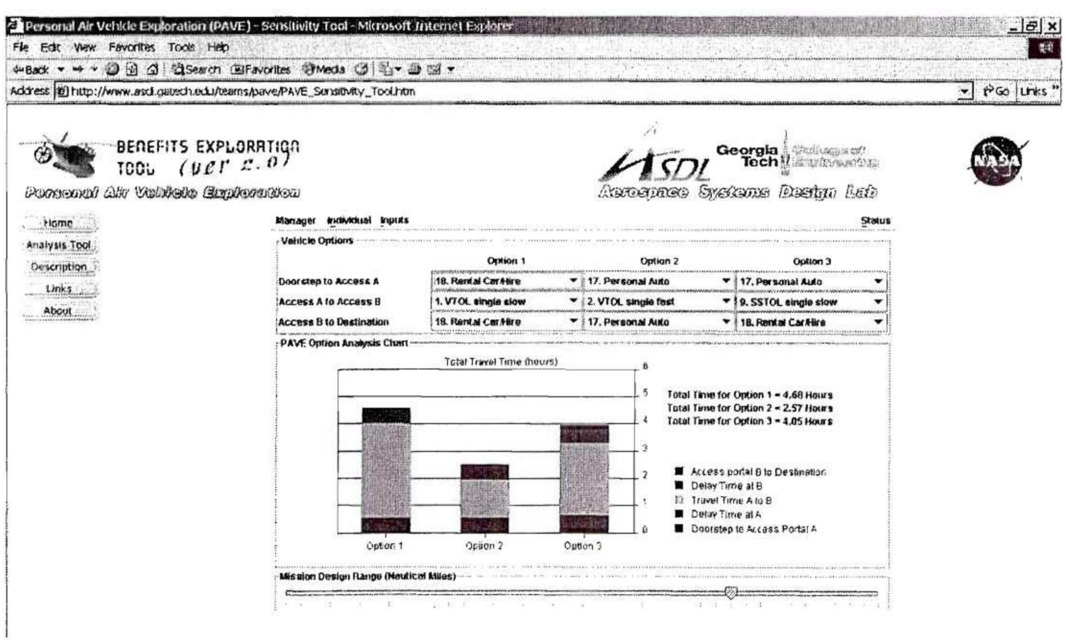


Figure 32: Mission Analysis Element of PAV JAVA Applet

Also, apart from analyzing the Travel Time, the user can analyze the Productivity Index of each vehicle for that mission. The Productivity Index is a way to standardize the productivity of a vehicle. It is calculated by multiplying the payload by the block speed – total travel distance over total mission time – which is subsequently divided by the sum of the empty weight plus the fuel weight. The units are miles per hour. The *Mission Analysis* tab uses basic data from the vehicles to be analyzed. As of the time of writing of this report, most of the data fields of the advanced concepts are empty. For the future, as more information is gathered for these vehicles, the more accurate the analysis will become.

Cash Flow Analysis Applet Element

The Cash Flow Analysis is meant to be an easy way of estimating the affordability of a PAV over an existing baseline transportation option. It was described in detail in the previous section. Four items must be known about the vehicle: the acquisition cost, the direct operating cost, the time saved, and the value of time of the user. When a user clicks on the Cash Flow tab, the graphic illustrated in Figure 33 is displayed. Explanatory information about cash flow analysis is also available on the web site by clicking on the Description tab in the toolbar.

The Cash Flow cannot be computed for the airliner nor the rental or personal automobile. If the user selects either one of those choices in the Mission Tab and accesses the Cash Flow tab, an error message will inform him or her that their vehicle choice is invalid for the Cash Flow analysis. The vehicle selections of these two tabs are linked and the values are maintained as long as the user has the applet running.

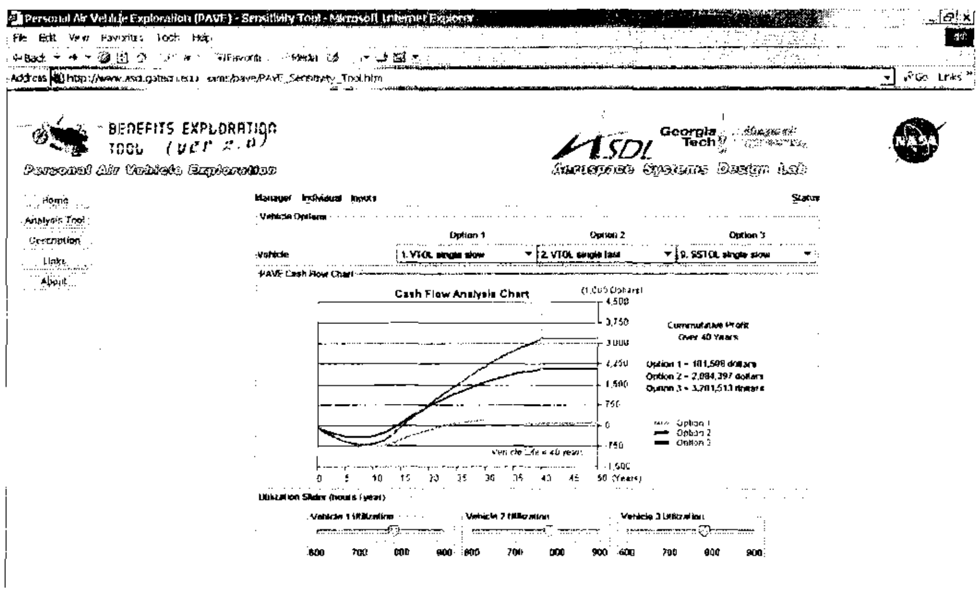


Figure 33: Cash Flow Element of the PAV JAVA Applet

The Cash Flow tab is mainly a JAVA version of the Cash Flow developed in Excel©. The main change is the way the user interacts with the tool. As in the Mission Analysis, the user inputs the utilization through the use of a slide bar. The user can change the values of some of the variables in the Inputs tab, including the user's salary, the time saving coefficient, the vehicle lifespan, etc. Future versions should also include a dynamic capability to change key assumptions at any time. For example, in the future, when more and more people will be using PAVs, the waiting times at portals would increase and therefore the time savings would decrease. If the time savings decrease, the benefits of using a PAV decrease. Therefore, less people would be attracted to buy PAVs. The opposite effect then occurs, with people who wait less than previously expected, and so on. Since the Cash Flow Analysis works over a period of 40 years, this factor should be taken into account.

Technology K-Factor Analysis Applet Element

The *Technology K-Factor* applet allows users to simulate technology advances that improve performance, cost, etc. This tab is intended to be used by the developers and R&D managers of future PAVs. Companies considering developing such vehicles might be interested in evaluating how future technologies might affect the characteristics of the vehicle. Regression equations that have been computed offline (in this case by ASDL's rotorcraft sizing code) underlie this applet element. The inputs to these equations are the so-called K-Factors, or generic technology metrics for a given class of vehicles or systems. Using the K-Factor approach, the effect on the dependent variables (responses) can be easily visualized by varying the different technology factors. In the future more technologies can be included to add more flexibility and span to the analysis. The more regression equations are developed, the more vehicles could be included. A snapshot of this important accomplishment appears in Figure 34.

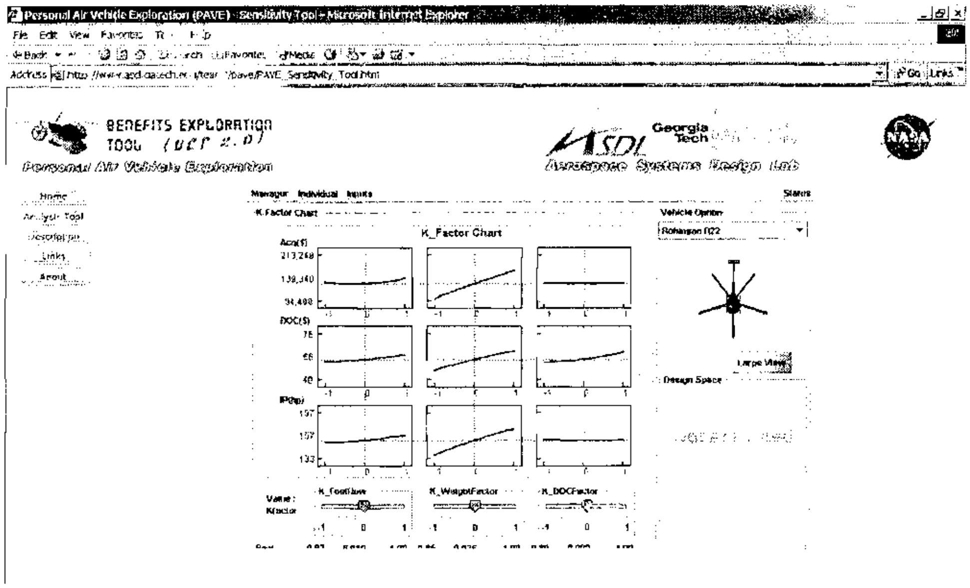


Figure 34: K-Factor Element of the PAV JAVA Applet

Travel Analysis Applet Element

The Travel Analysis tab offers the user the opportunity to evaluate the long distance travel missions in a more detailed manner. In this analysis, the user selects through with two drop down menus: the departure and destination cities respectively. As in the Mission and Cash Flow tabs, three vehicles are compared. The selection of the vehicles is imported from the values established in the Mission tab. In future versions another vehicle selection panel such as the one in the Mission Analysis tab could be added.

In this tab, the user can also specify what his or her specific case in each city is. They can either use the default average values -- which are still being collected for the mayor US cities -- or they can input their own values. According to the vehicle selected, the trip will have different number of legs. For example, if the user is comparing a "CTOL single slow" (Lancair) to a "VTOL single slow" (R-22/R-44) the helicopter will have to refuel more often than the airplane. Each stop carries a time delay, increasing the total time to complete the mission. The time delay at each stop is currently set at 30 minutes; future versions will allow the user to vary this time.

Monte Carlo Analysis Applet Element

The Monte Carlo Simulation is a statistical tool to assess probabilistic features during the designs. The simulation also employs the same K-factor regression equations described previously. In this case, the tool generates random input values for the factors according to assigned probability distribution for each of the inputs. The response from each input set is obtained by evaluating the respective regression equation. After a defined number of these random simulations are run, distributions are obtained for each of the responses. By using Monte Carlo simulation, uncertainty involved in the resultant design can be captured by defining uncertainty involved in the technology variables. Most probable design and degree of deviation can be illustrated by the PDF (probability density function) and the possibility of achieving the target value can be shown in the CDF (cumulative distribution function). A snapshot of the Monte Carlo capability is shown in Figure 35.

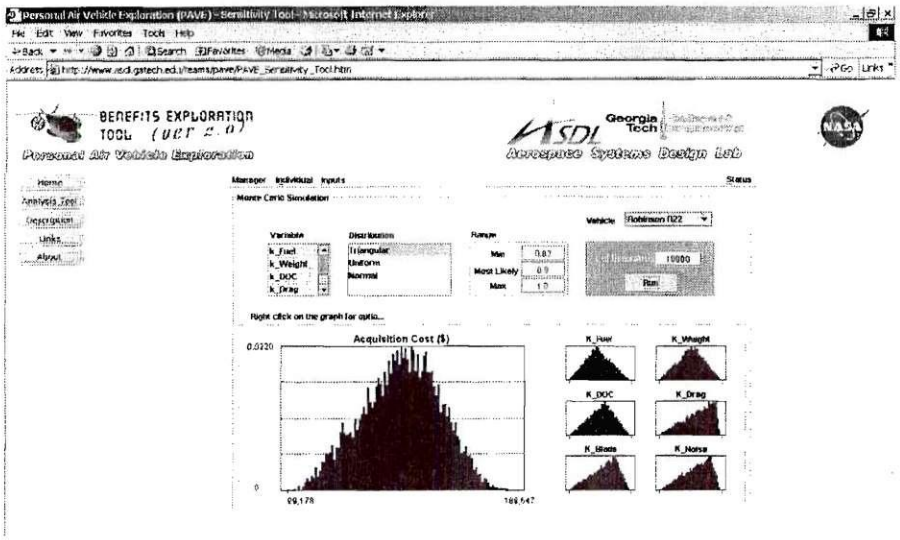


Figure 35: Monte Carlo Element of the PAV JAVA Applet

Recommendations for Future Work

In looking to the possible future developments, the primacy of the fact that the tool is mainly designed for the average college educated American must be remembered. It is not meant to be a purely engineering tool. Although some aspects of it are highly technical, the bulk of it should be intuitively easy to operate. If a user from the public feels the tool is too complicated, he or she might loose interest in the entire PAV topic.

The initial idea for the web-based tool was to follow the developments of the spreadsheet-based tool. As new analysis options are developed in the main spreadsheet, the "web-based team" must evaluate how to integrate them. Since the web-based tool should be intuitively easy to use, the approaches taken by the spreadsheet team might not be the most suitable ones, particularly the input-output methods (i.e. use slider bars instead of text cells, a chart instead of a column of numerical data, etc). They should be adapted in such a way as to fulfill the same task, but at the same time be simple to interact with. Further, as with the spreadsheet based tool, this tool will only be completely accurate once all the vehicle options are designed and tested. Until then it will include a large part of guesswork and approximations. Special care should be taken in trying to ensure that the RSEs are being used within the ranges for which they were created.

Finally, knowing that Personal Air Vehicles might not see a general use for another decade or two, this interactive web-based tool can be understood as a first step in trying to familiarize the public with the benefits they will provide. In order to convince the public, the idea has to seem affordable; therefore, the web site should convey this idea that PAVs are not just for eccentric multi-millionaires. This "familiarization" task is the main focus of the web site, to familiarize the public with Personal Air Vehicles and help them explore possible options. It cannot be stressed enough that this site should be intuitively easy to use and explore.

2. Advanced Concept Rotorcraft Development

There were several tracks pursued under the general topic of advanced rotorcraft for PAV. First, a new concept has been studied that was not included in the previous concept database. It is the CarterCopter. Second, parametric environments have been formed around the most promising rotorcraft vehicles identified in last year's studies. ASDL created detailed sizing/synthesis models for advanced concept versions of the Robinson family of light helicopters as well as the Groen Bros. Hawk4 autogyro. This work has now been extended through the creation of response surface equations (RSEs) around these concepts. The input factors to the RSEs are a mix of sizing, technology, and requirement variables. As such, the parametric environment embodied by these equations is termed a Unified Tradeoff Environment (UTE). Using the UTE, tradeoffs can be explored with various PAV scenarios between, for example, the relaxation of certain requirements vs. the infusion of particular technologies. One particularly interesting use of this capability is presented in this report. It is an exploration of uncertainty for two different concepts- the R-44 and the Hawk 4- utilizing the Joint Probabilistic Decision-Making (JPDM) environment.

2.1. Initial Study of a New Advanced Vehicle- The CarterCopter

The revolutionary CarterCopter gyroplane, shown in Figure 36, has been analyzed as a promising advanced rotorcraft concept and a potential "good match" for likely PAV mission profiles. A brief summary of the configuration's attributes and the results of ASDL's initial computational modeling and analysis are detailed in the next paragraphs. More detailed information on the technology demonstrator concept can be found at www.cartercopters.com. The CarterCopter was originally designed and built by Jay Carter Jr., chief executive officer and principal designer of CarterCopters, LLC. We are indebted to Mr. Carter for his assistance in providing to us the data needed for our modeling efforts.

Figure 36 : Three view of CarterCopter Gyroplane

Why is this concept such a potential "winner" for PAV? It has been claimed that this vehicle is able to take off and land vertically, fly at low speeds like a helicopter, and still be able to match the high speeds, long range, and high altitudes typical of a fixed wing aircraft. This is quite a statement. In general, the technical ideas behind such remarkable performance characteristics might be accomplished are summarized as follows.

- At high forward speed, the rotor will be slowed down to prevent the advancing blades from reaching a velocity near the speed of sound. Furthermore, by providing all the lift with a wing, resultant rotor unloading can prevent the retreating blade from stalling.
- The profile horsepower required for the rotor can be reduced by dropping the rotor RPM (it is essentially a function of RPM^3).
- The profile drag reduction is obtained by reducing the lifting surface drag to the minimum size necessary to support the aircraft. To keep the induced drag as low as practical, the wing span, which affects the induced drag by the inverse of the span required, can be small, since the rotor provides the required lift at slow and intermediate speeds. As s result, the wing can be very small and still provide the necessary lift for cruise conditions. ***The wing is optimized for cruise, not compromised for take-off and landing!***
- By using the compound turbocharged water-cooled piston engine, horsepower ratings at high altitudes can be maintained and horsepower needed in thin air can be obtained.
- The centrifugal force from 50lb of depleted uranium in each blade tip helps keep the rotor rigid and stable at reduced RPM and high forward speeds.

With data provided by CarterCopter, LLC., and from other sources, the flight vehicle's performance has been investigated using a spreadsheet analysis tool provided by CarterCopter, LLC. The ASDL's gyroplane analysis capabilities (embodied in the Georgia Tech Preliminary Design Program, GTPDP) has also been used. One of the first primary findings is that the trim analysis module of CarterCopter's code is different from that of ASDL's. The former uses a *power equilibrium* formula typical of helicopter analysis, while the latter uses a *force equilibrium* formula that is more similar to fixed wing aircraft analysis. Thus, initially similar results were not obtainable for all cases: Nevertheless, some cases were comparable, after an appropriate set of assumptions were made. This is demonstrated numerically in the following case.

The following analysis case shows that similar trim results are obtainable with the list of assumptions used in ASDL's analysis program. The assumptions are listed below, followed by the trim results in Table 7. Good agreement with CarterCopter figures are shown for a case where forward flight is at 175 mph and gross weight is 3100 lb.

Assumptions Required to Match Trim Condition for CarterCopter in GTPDP program

- Fixed Tip Speed = RPM 200
- Fixed Collective Pitch Angle = 0.0 deg
- Fixed Shaft Tile Angle = 7.04 deg
- Flat Plate Drag Area = 2 ft^2
- Fixed Horizontal Tail Lift = -306 lbs
- Fixed Wing Angle of Attack wrt Wind = 3.9 deg
- Total Wing Drag Adjustment using Reduction Factor

Table 7 : Comparison of Trim Results for CarterCopter Gyroplane (3100 lbs, 175 mph)

ITEM	GTPDP Analysis	CarterCopter Analysis
Tip Path Plane Angle (deg)	3.9	3.9
Fuselage Pitch Angle (deg)	-4.9	-5.0
Flapping Angle (deg)	1.8	1.85
Wing CL	0.45	0.45
Wing Lift (lbs)	2683.6	2666
Wing Drag (lbs)	30.4	30
Thrust (lbs)	239.2	241
Rotor Lift (lbs)	745.7	761
Main Rotor Power (HP)	25.1	24.8

Even though a high number of cases cannot currently be matched due to the difference in the trim analysis module mentioned previously, the trim results that were obtained do not seem to be differ significantly. However, the drag of the aircraft seems to be low and a proper operation of the rotor at a high advance ratio may cause problems, especially when considering the blade dynamics and loads. The vehicle may indeed fly as claimed by *CarterCopter, LLC if: 1) the flat plate drag area and wing aerodynamic characteristics are verified to be achievable and 2) high forward flight with low RPM control is indeed possible.* ***Thus, while a number of issues remain to be verified, it seems that the CarterCopter is a promising configurations for PAV application, based on the concept itself and these initial performance results.***

2.2. Probabilistic, Advanced Technology Exploration

Assessing the State-of-Affairs

In assessing the current PAV landscape, the following question is posed: What evolutionary and revolutionary concepts/technologies have the highest chance to be transformed into a successful PAVs? The process of exploring the viable concepts is both science and art. Since this is a jump from the existing technology, extensive brainstorming and "out of the box" thinking is required. ASDL has performed research to explore the current state of affairs with respect to rotorcraft technology.

The following are existing rotorcraft concepts that are or have been studied by our team for PAV: Robinson R22, Robinson R44, Groen Brother's Hawk 4, Carter Copter, and a Dual mode concept (developed at GATech in a AHS student competition). Extensive brainstorming was done to arrive at the list of features that would embody an attractive PAV and provide a means to measure the shortfall of existing vehicles. These features can also be called customer requirements or the "user wants". The previously mentioned vehicles have been examined from the point of view of these features shown below.

Speed	Price
Cost	Noise
Comfort	Reliability
Maintainability	Ease of flight
Take off length and	Mobility
Capacity	Emission
Safety	

A radar diagram (sometimes called a "spidergram") comparing the 5 current concepts under study is shown in Figure 37. This type of comparison is useful because it helps in determining which rotorcraft performs the best in each area. When all the best concepts have been identified, they can be combined together to give a notional PAV technology. In the radar diagram, the outer ring is the "aspiration space", indicated by a notional value of 10.

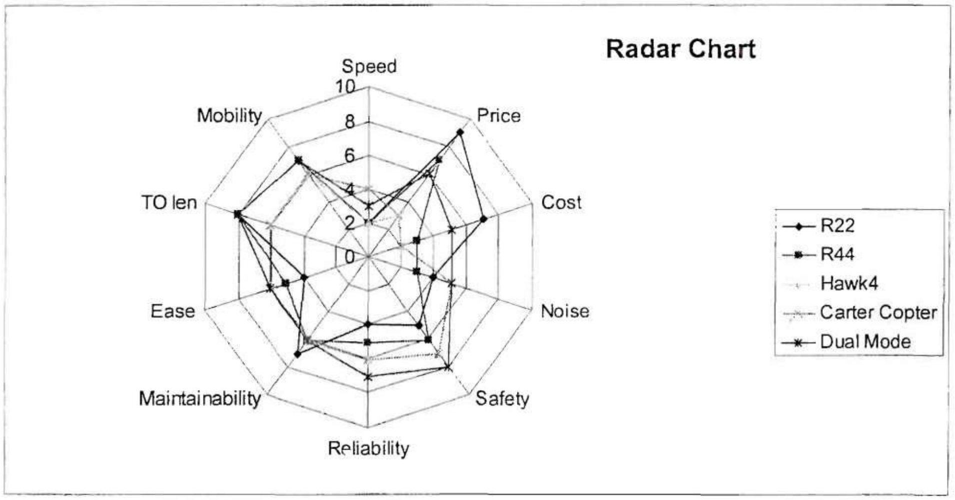


Figure 37: Radar Diagram or "Spidergram" for Potential Rotorcraft PAV Attributes

As can be seen in Figure 37, the R-22 is the best option from price, cost and maintainability point of view but does poorly in ease of flight, reliability and safety. On the other hand, the dual mode concept developed in Georgia Tech performs very well in reliability and safety but is not very feasible from cost and speed point of view. This kind of study can help identify the best options within the existing technologies. Subsequently, evolutionary or revolutionary technologies can be included on top of the best existing concepts. All the finest options can be combined together to generate an ideal PAV configuration. Some identified examples of both types of technologies are shown in Table 8 and Table 9.

Table 8: Summary of Evolutionary Technologies for Rotorcraft

EVOLUTIONARY TECHNOLOGY	ADVANTAGES
HUMAN FACTOR	Comfort
Auto Pilot / SAS	Ease of flight, more can fly
Accident prevention	Safety
New Material	Low price, better speed, reliability
New Engine technology	Low price, better speed, maintainability
Active noise control	Low noise
Aerodynamic blade design	Better speed, low DOC, noise
Reaction Driven rotor	Low noise, better reliability
All weather compatibility	Reliability
Alternative power source	Reliability
Traffic monitoring technology	Safety, reliability
Advanced mobility concepts	Better mobility, higher speed

Table 9: Summary of Revolutionary Technologies'

REVOLUTIONARY TECHNOLOGY	ADVANTAGES
New Rotor system	Low noise, safety
New Engine	More power, speed, less fuel consumption
Compounding	Wing, span -- better overall performance

Methodology for Exploring the Impact of Advanced Technologies

A technique for assessing the impact of the infusion of identified advanced technologies (such as those above) has been created and is described here. Two helicopter configurations, R22/R44, and one autogyro configuration, the Hawk4, have been selected as baseline concepts for the creation of the Unified Tradeoff Environments (UTE) for technology studies. The UTE allows investigation of potential technologies that may improve technical feasibility and economic viability of the vehicles.

The impact of a technology can be qualitatively assessed with technology metric "k" factors, which modify disciplinary technical metrics. A "k" factor is a multiplier on a given disciplinary metric that is used to simulate generic application of advanced technologies. This factor can later on be mapped to actual technologies being applied. The simulation of advanced technologies in the form of "k" factors enables a dynamic mapping and visualization of the Technology Impact Forecasting (TIF) space. The "k" factors that quantified the relevant rotorcraft technologies are listed in Table 10:

Table 10: List of Technology K-factors and Their Purpose

Technology Arears	"k" Factors	Description
Engine characteristics	k_ffr	k factor for the engine fuel flow ratio
Component weight	k_wrtrg	k factor for the rotor weight
	k_wprng1	k factor for the engine weight
	k_wprng2	k factor for the dynamic system weight
	k_wbdyg	k factor for the airframe weight
Direct operating cost	k_xc1	k factor for the maintenance burden
	k_af	k factor for the airframe overhaul
	k_tbo	k factor for the engine TBO
	k_tbods	k factor for the dynamic system TBO
Aerodynamic characteristics	k_efpda	k factor for the flat plate drag area
	k_cl	k factor for the blade lift coefficient
	k_cd	k factor for the blade drag coefficient
Power available and required	k_stal	k factor for the rotor stall power
	k_comp	k factor for the compressibility power
Noise characteristics	k_noise	k factor for the noise

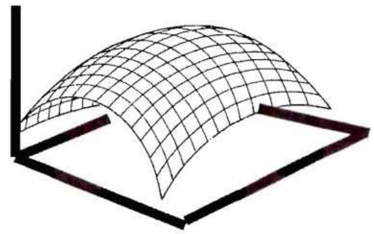
When studying revolutionary concepts, which may not be fielded until many years' in the future, one recurring difficulty is dealing with the possible variation in requirements as well as technologies as time progresses. Thus, a capability to model and visualize the interactions between PAV requirements and advanced rotorcraft vehicle characteristics is certainly desired. Such a capability has been achieved through the combined use of the GTPDP computer model and the Response Surface Methodology (RSM).

The Georgia Tech Preliminary Design Program (GTPDP) is an "in-house" development of a helicopter design code based on the original SSP1/SSP2 (Single Rotor Helicopter Designing and Performance Programs) codes.

GTPDP allows vehicle and component sizing, mission analysis, performance estimation, cost analysis, design optimization, and trade-off studies.

RSM is a multivariate regression technique developed to model the response of a complex system using a simplified equation. It is based on the Design of Experiments (DoE) methodology, which gives the maximum power for a given amount of experimental effort. The regression data is obtained intelligently through the (DoE) techniques. Typically, the response is modeled using a second-order quadratic equation of the form:

$$R = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j$$



Where,

b_i are regression coefficients for the first degree terms

b_{ii} are coefficients for the pure quadratic terms

b_{ij} are the coefficients for the cross-product terms

In this study, the variables of interest are first identified as the input variables and are listed in Table 11. Twelve variables are selected, with some clearly being technology "k" factors (e.g. weight factors, DOC factor) as described before, while others are requirements (e.g. payload, range). Minimum and maximum values are selected for each of the 12 variables to bound the space to be modeled. For completeness, the corresponding variable name from the GTPDP program is also included. The values are chosen according to the PAV mission requirements and the quantification of the infused advanced technologies. The responses to be tracked are shown in Table 12.

Table 11: UTE Variable Definitions and Ranges of Variability

			R22		R44		HAWK4	
	Description	GTPDP Variable	min	max	min	max	min	max
var1	Fuel Flow Ratio	PKFFR	0.82	1	0.8	1	0.82	1
var2	Weight Factors	PKWRTRG	0.85	1	0.8	1	0.85	1
		PKWPRNG1	0.85	1	0.8	1	0.85	1
		PKWPRNG2	0.85	1	0.8	1	0.85	1
		PKBDYG	0.85	1	0.8	1	0.85	1
var3	DOC Factors	PKXC1	0.8	1	0.8	1	0.8	1
		PKAF	0.8	1	0.8	1	0.8	1
		PKTBO	0.8	1	0.8	1	0.8	1
		PKTBODS	0.8	1	0.8	1	0.8	1
var4	Airframe Drag Area	PKEFPDA	0.86	1	0.8	1	0.86	1
var5	Blade Parameters	PKCLALFB	0.8	1	0.8	1	0.8	1
		PKCDO	0.8	1	0.8	1	0.8	1
		PKSTAL	0.8	1	0.8	1	0.8	1
		PKCOMP	0.8	1	0.8	1	0.8	1
var6	Noise Factor	PKNOISE	0.8	1	0.8	1	0.8	1
var7	Disk Loading	DL	2.65	2.85	2.6	2.9	2.45	2.65
var8	Power Loading	PL	7.5	9.5	8	11	7.5	9.5
var9	Payload (lb)	RPL	200	600	600	1600	200	1600
var10	Mission Range (nm)	RANGE	100	500	100	500	100	500
var11	Cruise Speed (kts)	V3	80	130	90	140	100	150
var12	Utilization (hr/yr)	BHPY	260	1300	260	1300	260	1300

By using the DoE technique, a number of experiments are generated, resulting in different combinations of the values of the 12 input variables. After all the required runs of GTPDP have been completed, the resulting data is used to regress relationships of the responses to the 12 inputs. These relationships take the form of 2nd order polynomial equations called Response Surface Equations (RSEs). It is important to note that the RSEs are only valid within the hyperspace defined by the variable ranges listed in Table 11.

Table 12: Response to be Tracked in UTE

Variable	Description
GW	Gross Weight
WEMPTY	Empty Weight
WFUEL	Fuel Weight
ENGINE	Installed Power
VMAX	Maximum Cruise Speed
MTIME	Total Mission Time
AC	Acquisition Cost
DOC	Direct Operating Costs

The RSEs for the Hawk4 interactively represented by the Prediction Profile are shown in Figure 38. The Prediction Profile is a very powerful visualization and analysis tool. Through this tool, one can investigate the design space by manipulating the design variables to determine if an objective can be met. It indicates the trends of the response variables to the inputs, as well as their sensitivity. Relatively flat trends indicate that a particular response is not sensitive to a given variable, while large slope indicate that a response is highly dependent on a particular variable.

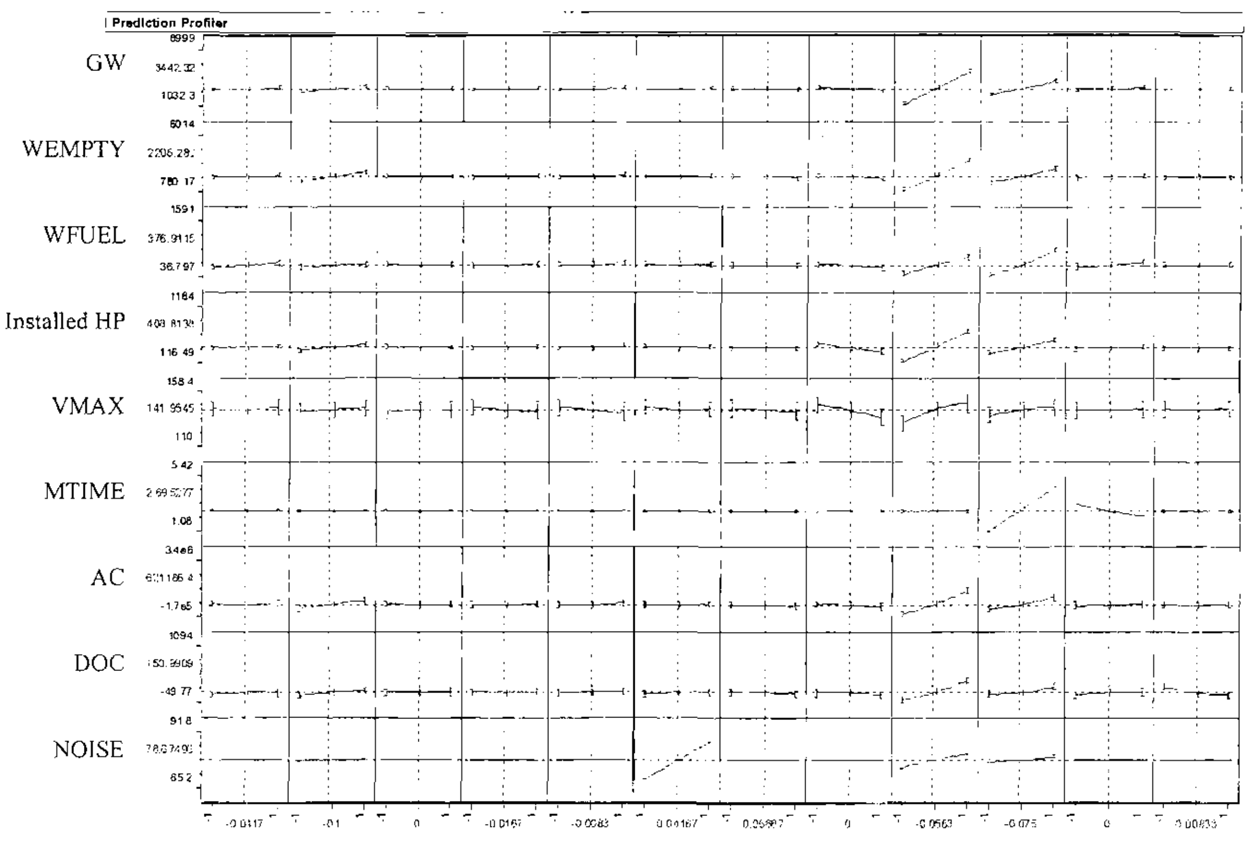


Figure 38: UTE for *Hawk4* : Response Surface Equations (RSEs)

Identification of the areas of greatest importance can be achieved. For example, the significant impact of the payload and range requirements relative to the technology "k" factors can be observed by noting the large slopes for the sensitivity of nearly all the responses to those two input factors. Among the "k" factors themselves, for the selected ranges of variation, the weight factors have a lightly larger impact on most key responses (such as gross weight and acquisition cost). This indicates that those technologies associated with weight reduction should be targeted for investigation and/or investment. Further, since interaction effects between factors are modeled, a change in the setting of one factor will change the sensitivity of all the other factors according to the strength and polarity of that particular interaction.

For further study, the viability of each advanced technology version is measured using Joint Probabilistic Decision Making (JPDM) technique, which was developed at Aerospace System Design Laboratory (ASDL). Among the decision-making techniques, traditional single criterion approaches fail to account for the entire system. Furthermore, current multi-criteria approaches require deterministic information for the system and environment, information not typically available at conceptual or preliminary phases. Moreover, the use of the new technologies adds more uncertainty to the design process due to readiness or availability issuesJPDM overcomes these shortcomings by incorporating a multi-criteria and a probabilistic approach to systems design and can accurately estimate the probability of satisfying the criteria concurrently. There are two models in JPDM technique called Joint Probability Model (JPM) and Empirical Distribution Function (EDF). JMP is an analytical approach while the EDF relies on empirical data used to build the joint probability mass function. JPDM uses Probability of Success (POS) as the objective function:

$$\begin{aligned} \boldsymbol{POS} &= P(Criteria_1 \in Constrain_1, \mathrm{Ctiteria}_2 \in Constrain_2) \\ &= \tfrac{1}{10{,}000} \sum_{i=1}^{10{,}000} I(Criteria_1 \in Constrain_1, \mathrm{Ctiteria}_2 \in Constrain_2) \end{aligned}$$

Where: $\mathrm{Criteria}_1$ and $\mathrm{Criteria}_2$ are two system objectives that are investigated

$\mathrm{Constain}_1$ and $\mathrm{Constain}_2$ are limitation for the two criteria and construct the area of interest

The two-dimensional representation of JPDM environment is shown in Figure 39. For this study, data are generated with the RSEs through the Monte Carlo Simulation and then used for an Empirical Distribution Function. Uncertainty is propagated to the system level by defining appropriate probability distributions to uncertain mission requirements, vehicle attributes and infused technology. The variable distributions for the particular problem at hand are listed in Table 13.

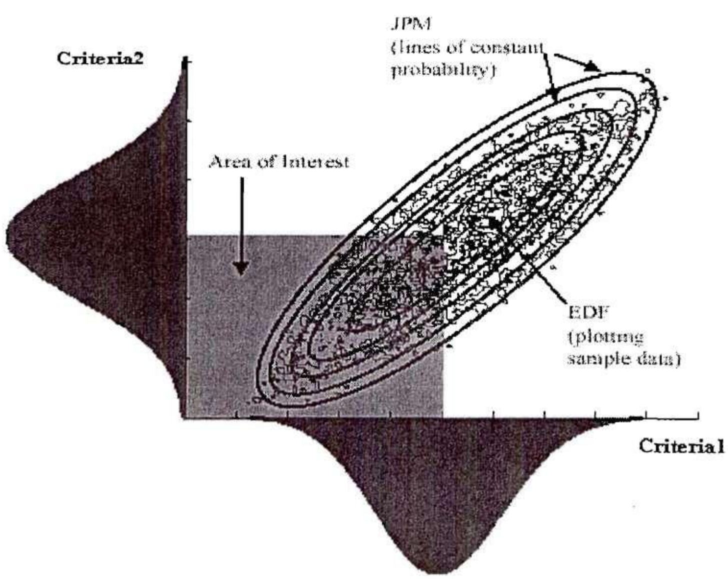


Figure 39: Graphical Image of JPDM Environment

Table 13 : Noise Variable Distributions

Noise Variable	Unit	Distribution Type	Parameters		
			R22	R44	Hawk4
Fuel Flow Ratio	%	Beta	$\alpha = 8, \beta = 2$	$\alpha = 8, \beta = 2$	$\alpha = 8, \beta = 2$
Weight Factor	%	Beta	$\alpha = 8, \beta = 2$	$\alpha = 8, \beta = 2$	$\alpha = 8, \beta = 2$
DOC Factor	%	Beta	$\alpha = 5, \beta = 3$	$\alpha = 5, \beta = 3$	$\alpha = 5, \beta = 3$
Airframe Drag Area	%	Beta	$\alpha = 3, \beta = 5$	$\alpha = 3, \beta = 5$	$\alpha = 3, \beta = 5$
Blade Parameter	%	Beta	$\alpha = 5, \beta = 3$	$\alpha = 5, \beta = 3$	$\alpha = 5, \beta = 3$
Noise Factor	%	Beta	$\alpha = 2, \beta = 8$	$\alpha = 2, \beta = 8$	$\alpha = 2, \beta = 8$
Disk Loading	lbs/sqft	Uinform	2.65 - 2.85	2.6 - 2.9	2.45 - 2.65
Power Loading	lbs/hp	Uinform	7.5 - 9.5	8.0 - 11.0	7.5 - 11.0
Payload	lbs	Uinform	200 - 600	600 - 1600	200 - 1600
Mission Range	nm	Uinform	100 - 500	100 - 500	100 - 500
Utilization	hrs/year	Uinform	260 - 1300	260 - 1300	260 - 1300
Doorstep to Portal A Time	hrs	Normal	$\mu = 0.1, \sigma = 0.01$	$\mu = 0.1, \sigma = 0.01$	$\mu = 0.2, \sigma = 0.02$
Wait Time at Portal A	hrs	Normal	$\mu = 0.5, \sigma = 0.05$	$\mu = 0.5, \sigma = 0.05$	$\mu = 0.5, \sigma = 0.05$
Wait Time at Portal B	hrs	Normal	$\mu = 0.5, \sigma = 0.05$	$\mu = 0.5, \sigma = 0.05$	$\mu = 0.5, \sigma = 0.05$
Portal B to Destination Time	hrs	Normal	$\mu = 0.1, \sigma = 0.01$	$\mu = 0.1, \sigma = 0.01$	$\mu = 0.2, \sigma = 0.02$

Viability of a design concept is measured by the probability of satisfying certain desired levels of the doorstep to destination time (TT), direct operating cost (DOC) and noise. All the criteria are desired to be as small as possible, so 0 as a minimum value is assigned to all the criteria. The maximum value that needs to be satisfied is identified as 4 hrs, 150 $/hr, 80 db for doorstep to destination time, DOC and noise respectively. The results are shown in Figure 40.

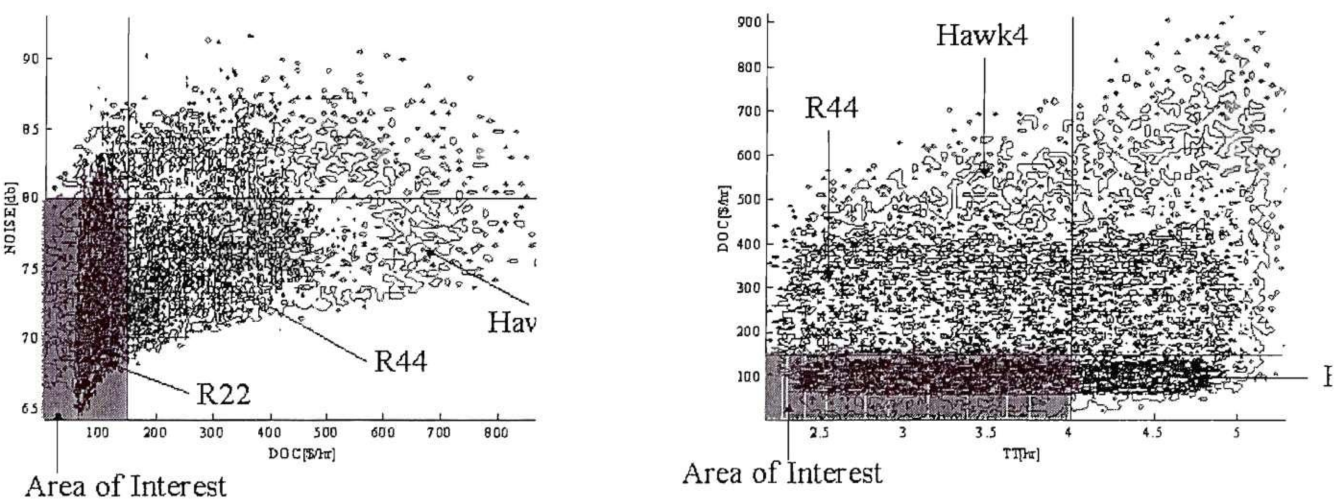


Figure 40: Joint Probability Distributions (a: Criteria: DOC and Noise; b: Criteria: Doorstep to Destination Time)

The Probability of Success (POS) for each concept can be calculated by JPDM and is shown in Table 14. The highest Probability of Success is obtained with of the R22 advanced technology version is the highest. This indicates the R22 version has more viability when the alternatives are measured by the criteria of DOC, doorstep to destination and noise.

Table 14: Joint POS and Univariate Probabilities for Each Alternative

Alternatives	*Joint POS*	P(*TT*<*4* hr)	P(*DOC*<150 $/hr)	P(*Noise* < 80 db)
R22	0.6659	0.6762	1	0.9812
R44	0.1896	0.6639	0.2383	0.8997
Hawk4	0.2036	0.5825	0.3032	0.8784

3. Circulation Control Channel Wing Analysis Tool

Submitted Under Separate Cover, along with electronic form of tool and User's Guide

4. Propeller/Ducted Fan Analysis Tool

Submitted Under Separate Cover, along with electronic form of tool and User's Guide